Small Wind Turbine Generator Condition Monitoring: Test Rig and Preliminary Analysis

Cai, Hongwei

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Small Wind Turbine Generator Condition Monitoring:
Test Rig and Preliminary Analysis

by

Hongwei Cai

A THESIS
SUBMITTED TO THE FACULTY OF GRADUATE STUDIES
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Abstract

In order to simulate small wind turbine generators working at variable speed and develop reliable condition monitoring and fault diagnosis techniques, a test rig based on a 500 W permanent magnet generator was built. A suitable accelerometer was selected and successfully used for vibration signal collection. The best sensor location is at 6 o’clock on the outside rim of bearing housing. Mechanical and electrical imbalances were simulated. Preliminary analyses of both imbalances under constant speed were introduced. Due to the variable speed nature of wind turbine operation, time-frequency analysis tools have been accepted as key signal processing tools for such application. Short time Fourier transform (STFT), continuous wavelet transform (CWT) analysis and order analysis were performed and compared on data acquired from the test rig for preliminary analysis of bearing. Order analysis proved to be a simple, intuitive and reliable technique for vibration analysis under variable speed.
Acknowledgements

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Finally, I express my special thanks to my dear family for their supports and encouragement.
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<td>FFT</td>
<td>fast Fourier transform</td>
</tr>
<tr>
<td>PMG</td>
<td>permanent magnet generator</td>
</tr>
<tr>
<td>VFD</td>
<td>variable frequency drive</td>
</tr>
<tr>
<td>STFT</td>
<td>short time Fourier transform</td>
</tr>
<tr>
<td>CWT</td>
<td>continuous wavelet transform</td>
</tr>
<tr>
<td>TSR</td>
<td>tip speed ratio</td>
</tr>
<tr>
<td>SK</td>
<td>spectral kurtosis</td>
</tr>
<tr>
<td>P</td>
<td>power</td>
</tr>
<tr>
<td>ω</td>
<td>shaft rotational speed in rpm</td>
</tr>
<tr>
<td>f_r</td>
<td>shaft speed in Hz</td>
</tr>
<tr>
<td>f rv</td>
<td>shaft speed reading from VFD in Hz</td>
</tr>
<tr>
<td>f_c</td>
<td>cage rotational frequency in Hz</td>
</tr>
<tr>
<td>f bpfi</td>
<td>ball pass frequency of inner race in Hz</td>
</tr>
<tr>
<td>f b pfo</td>
<td>ball pass frequency of outer race in Hz</td>
</tr>
<tr>
<td>f bsf</td>
<td>ball spin frequency in Hz</td>
</tr>
<tr>
<td>D_b</td>
<td>ball diameter</td>
</tr>
<tr>
<td>D_c</td>
<td>pitch diameter</td>
</tr>
<tr>
<td>Z</td>
<td>number of the balls</td>
</tr>
<tr>
<td>θ</td>
<td>contact angle</td>
</tr>
<tr>
<td>A</td>
<td>amplitude</td>
</tr>
<tr>
<td>φ</td>
<td>phase angle</td>
</tr>
<tr>
<td>f_s</td>
<td>sampling frequency</td>
</tr>
<tr>
<td>F max</td>
<td>the highest frequency that can be analyzed</td>
</tr>
<tr>
<td>Δ f</td>
<td>frequency resolution</td>
</tr>
<tr>
<td>T</td>
<td>window size of the STFT in time domain</td>
</tr>
<tr>
<td>N</td>
<td>number of samples in the FFT</td>
</tr>
<tr>
<td>p</td>
<td>number of PMG poles</td>
</tr>
<tr>
<td>j</td>
<td>corresponding level of decomposition</td>
</tr>
<tr>
<td>k</td>
<td>order of the node position at that specific level</td>
</tr>
<tr>
<td>E jk</td>
<td>energy at wavelet packet node (j, k)</td>
</tr>
<tr>
<td>1 X</td>
<td>shaft rotating speed</td>
</tr>
<tr>
<td>3.6 X</td>
<td>3.6 times shaft rotating speed</td>
</tr>
<tr>
<td>db3</td>
<td>Daubechies wavelet of order 3</td>
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Chapter One: Introduction

1.1 Background

With global warming on the rise, it is unavoidable to use renewable sources for electrical energy. During recent years, wind energy is considered as one of the viable renewable energy sources. Electricity production from the wind is growing over 20% annually. So the global market for wind energy is booming and is gaining importance across the globe [1]. The rapid growth of wind power technology and its increasingly important role in energy planning for Europe, the United States and Asia is remarkable [2]. In the future, more wind farms will be built offshore to utilise stronger winds and higher turbine speeds with less concern about noise production. To manage cost, there will be a strong demand for higher reliability with an absolute minimum requirement for onsite maintenance on wind turbines.

Wind energy is plentifully available. Large wind turbines are becoming an economical and practicable alternative to conventional fossil-fuelled power generation. Small wind turbines are commonly used for grid connection under feed-in tariff regimes, and for remote power systems.

Due to their variable load condition and harsh operating environment, wind turbines experience substantial failures [3]. Reliability of wind turbines is critical to extract the maximum amount of energy from the wind. In recent years, many efforts have been made to prevent failures [4, 5]. Nevertheless, gearbox, and to a lesser extent, generator failures continue to be a major issue with large wind turbines [6].

No assessment of the need for condition monitoring, or of implementation of it, for small wind turbines has been found in the literature. Small wind turbines have a reputation of being less reliable than larger ones, and are often used in remote locations for which maintenance is a major problem. Small wind turbines will gain more popularity in the remote region due to limited
hydrocarbon resources. It is critical to improve the reliability of small wind turbine in the remote locations. Meanwhile using small wind turbines has significant social effects for the long term. Furthermore, wind turbines of all sizes must operate at variable generator speed for maximum efficiency. Specifically, the wind turbine control system tries to maintain a constant optimum tip speed ratio (TSR) as the wind speed varies, which normally means making the generator speed proportional to the wind speed [7]. TSR is the ratio between the speed of the tip of a blade and the actual velocity of the wind. The TSR is of vital importance in the design of wind turbines because it determines the efficiency, with the optimum efficiency varying with blade design.

The signals collected from the wind turbine with speed variation are non-stationary. However, fault diagnosis techniques are still mainly based on the Fourier transform (FT), which do not perform very well with non-stationary signals. Therefore, it is highly desirable to develop effective and reliable condition monitoring and fault diagnosis techniques that address the variable speed nature of the applications.

1.2 Challenges

In order to develop condition monitoring techniques for small wind turbines, a test rig was built and tested. Several signal processing techniques were employed to recognize the condition change of the generator under constant and variable speed during the test. Major challenges include:

- Test rig should be set up to simulate a small permanent magnet generator (PMG) under variable running speed. Meanwhile, it must be capable of allowing the collection and analysis of stationary and non-stationary vibration signals and be useable for future research and development.
• It is difficult to select the suitable sensors for data collection and choose the best mounting location for it.

• It is desirable to effectively simulate faults for the bearings, mechanical and load imbalances.

• Traditional frequency analysis cannot be used with random speed variation due to random wind speeds. Time-frequency signal processing techniques are required to deal with non-stationary signals.

• The majority of electrical machines use ball or rolling element bearings and they are one of the most common causes of machine failure [3]. It is desired to find a method to detect a bearing fault with variable speed.

• It is desirable to find a method to detect mechanical and electrical imbalances at constant speed to serve as a baseline for experiments at varying speed.

1.3 Organization of the Thesis

The thesis is organized into six chapters, four appendices and a list of references:

• Chapter 2 reviews key literatures on wind turbine and, specifically generator, failures, condition monitoring techniques, test rig, signal processing techniques on bearing and imbalance faults. Then the objectives of the research are defined.

• Chapter 3 describes the experimental setups of the test rig. System design, mechanical design, instrumentation design and data acquisition system are presented in detail.

• Chapter 4 presents the preliminary analysis on generator operation under constant speed. Spectrum analysis was used to analyse the vibration signal from the rear generator bearing. The characteristic frequency of bearing outer race defect was shown as the first
significant peak. Spectrum comparison, wavelet power spectrum and voltage analysis were used to analyze the mechanical and electrical imbalances. A waterfall baseline was constructed for future machine condition monitoring.

- Chapter 5 presents three preliminary analyses on the generator with variable speed such as short time Fourier transform (STFT), continuous wavelet transform (CWT) and order analysis. Order analysis was successfully used for vibration analysis on wind turbine with non-stationary signal.

- Chapter 6 concludes the thesis with a summary of the results and the potential future work.
Chapter Two: Literature Review and Research Objectives

The literature on general wind turbine operation, failure modes, condition monitoring methods, test rig and signal processing techniques for wind turbines are reviewed. Nearly all the references consider large wind turbines, so particular attention is paid to the literature on small wind turbine faults. Then the research objectives are defined in detail based on the literature review.

2.1 Wind Turbine General

Based on cost and annual energy yield for a given wind regime, five different generator systems for wind turbines are compared, namely the doubly-fed induction generator with three-stage gearbox (DFIG3G), the direct-drive synchronous generator with electrical excitation (DDSG), the direct-drive permanent-magnet generator (DDPMG), the permanent-magnet generator with single stage gearbox (PMG1G), and the doubly-fed induction generator with single-stage gearbox (DFIG1G). For any generator, variable speed operation achieves the maximum power output by operating at constant tip speed ratio while the wind speed varies [7], which means the ideal generator speed is proportional to the wind speed. Time-frequency analysis tools have been accepted as key signal processing tools for such variable speed application. The DDPMG could be the best solution because it does not have brushes or a gearbox that wears and simpler power electronics. However, it is more expensive and usually heavier compared to generator systems with a gearbox. There is also the issue that permanent magnet materials have risen rapidly in cost but are now reasonably stable. Meanwhile, the size and mass of wind turbines grows rapidly with power capacity. Today’s high-power direct-drive generators are massive units that will need to become smaller to minimize costs [2].
IEC 61400-2 defines a small wind turbine as having a swept area of less than 200 m², which corresponds to a power output of about 50 kW [8]. Small wind turbines are used for remote power systems and single-user grid connections. The main generators used for small turbines are DDPMGs. No examples of small permanent magnet generators with a gearbox have been found so the direct drive aspect of DDPMGs will be assumed and the abbreviation PMG will be used.

2.2 Failure Modes

2.2.1 General

Most subsystems in wind turbines can fail during operation, including rotors and blades, pitch control systems, gearboxes and bearings, yaw systems, generators, power electronics, electric controls and brakes among others [9].

Tavner et al. [10] conducted a survey of large wind turbine failures over 11 years. The failure rates of fixed-speed, variable-speed-indirect-drive and variable-speed-direct-drive turbines were compared from the failure data for up to 4,000 turbines in Germany and more than 1,000 turbines in Denmark. The study concluded that there was a substantial increase of the failure rate of all electrical components over time although the failure rate of direct-drive wind turbines is reduced by eliminating the gearbox. However, the availability of direct-drive units should be higher than gearbox drives because the mean time to repair electrical components is lower than that of gearboxes [3]. Wilkinson et al. [11] mainly focused on further comparison of variable-speed and fixed-speed wind turbines documented in [10]. These studies showed similar results.
Common failure modes on large PMGs are armature faults, permanent magnetic faults and mechanical faults such as bearing failure and eccentricity of the machines [12]. This research focuses on bearing fault, mechanical and electrical imbalance faults for a small PMG.

2.2.2 Bearing Faults

Rolling element bearings are one of the most widely used components in machines and their failure is one of the most frequent reasons for machine breakdown. Failure surveys have reported that percentage failure by components in induction machines is typically: bearing related (40%), stator related (38%), rotor related (10%), and others (12%) [13].

Bearing faults constitute a significant percentage of all faults in gearboxes as well as generators [3, 4].

According to the stages in the fault development process, bearing faults can be categorized into two types [14] : 1) single-point fault, which is defined as a single and localized fault on an otherwise relatively undamaged bearing surface, and 2) generalized roughness, where the bearing surface has degraded considerably over a large area and becomes rough, irregular, or deformed. There is not much information available from the field to justify the statistic result for the two types of bearing failures.

Single-point faults in a ball bearing can occur in all components: the inner race, outer race, ball, and cage. A common example is a pit or spall. In spite of the name, a bearing can possess multiple single-point defects. The characteristic frequencies of a single-point fault in vibration measurements depend on the bearing geometry and rotating frequency. The configuration of a ball bearing and the theoretical fundamental characteristic frequencies of the four types of single-point faults in vibration measurements can be found in [15].
Generalized roughness does not generate characteristic frequencies in the vibration measurements [14]. There is no localized defect to be identified as the fault; rather, large areas of the bearing surface(s) have deteriorated. A common example of the generalized roughness is the overall surface roughness produced by a contamination or loss of lubricant, which does not develop from single-point faults. It produces unpredictable broadband changes in machine vibration. This type of bearing fault is not in the scope of this research.

It is highly desirable to detect bearing single-point faults and repair or replace the faulty bearing(s) in time to prevent further damage to other components of the system and to reduce the downtime of wind turbines. Furthermore, replacement of faulty bearings is an easier and cheaper task than replacing a complete gearbox or generator.

2.2.3 Mechanical Imbalance

Mechanical imbalance constitutes a significant portion of all faults in wind turbine generators [16]. A common mechanical imbalance in wind turbines is shaft/blade imbalance. A blade imbalance can be caused by errors in manufacturing and construction, icing, deformation due to aging, or wear and fatigue during the operation of the wind turbine. Components tend to shift and wear in varying degrees over time, causing imbalance on the rotating shaft/blades. Another common mechanical imbalance is torque asymmetry, which can be caused by several factors, including high wind shear and errors in the control mechanism. If the pitch of one blade is slightly different from the other two blades due to errors in the control mechanism, the torque on the rotating shaft will not be balanced, leading to torque asymmetry. Imbalance caused by torque asymmetry is not in the scope of this research.

Mechanical imbalance will have characteristic frequency of shaft rotating speed (referred to as the 1X) and mainly in the radial direction [17].
A small mechanical imbalance can cause significant consequences on the tower as well as the other components of the wind turbine. Effective mechanical imbalance diagnosis and condition monitoring techniques are of significant interest to the wind power industry. It is highly desired to detect mechanical imbalance to allow repair machine in the earlier stage of the problem.

2.2.4 Electrical Imbalance

Electrical faults occur either in the generator (e.g. stator winding fault), or in the circuit (e.g. circuit imbalance, short circuit and breaking of contact). The output of the generator will be disturbed.

One common electrical fault is circuit imbalance in the external load. It can be simulated by changing the phase resistances of the generator stator with the aid of a load bank connected to it. The twice slip frequency of an induction generator may be regarded as a characteristic frequency for detecting the electrical fault caused by imbalanced phase resistances through power signal collected [18]. No assessments of the need for detecting electrical circuit imbalance or of implementation of it are recognized for small wind turbines with PMGs.

Bearing fault, mechanical and electrical imbalance faults of PMG, which were investigated in the research, are three of the major faults in PMG.

2.3 Condition Monitoring Methods

Condition monitoring is based on being able to monitor the current condition and predict the future condition of machines while in operation. Thus it means that information must be obtained externally about internal effects while machines are in operation.
Vibration, temperature, chemical, electrical and discharge monitoring have proven successful for condition monitoring of rotating electrical machinery [19].

For wind turbine generators, vibration monitoring, acoustic emission, torque measurement, and electrical analysis have been widely investigated for fault diagnosis and condition monitoring [20].

Vibration measurement and spectrum analysis are typical choices for constant speed machinery monitoring and diagnostics. For variable-speed wind turbine operation, wavelet analysis has been recently accepted for feature extraction, as compared to faster Fourier transform (FFT) [3].

Acoustic emission has recently been considered a suitable development of classic vibration based methods, especially to detect incipient failures [3]. Lekou et al. [21] used acoustic emission combined with vibration, temperature and rotating speed data for health monitoring of large wind turbine gearboxes and bearings. Due to the high frequency requirement in acoustic emission measurement, the cost of data acquisition systems with high sampling rates needs to be considered.

Torque measurement has also been utilized for drive train fault detection, e.g. mass imbalance [22]. However, it is still not feasible to use torque measurement for drive train fault diagnosis and condition monitoring because torque sensors are usually expensive and difficult to install.

Approaches for detecting drive-train mechanical faults in wind turbines, using generator electrical signatures have been introduced in literature [23-25]. A rotor imbalance diagnosed using the terminal power signal of the generator was first introduced in [26]. Yang et al. [22] presented the electrical power analysis to diagnose mechanical faults of the wind turbines with
synchronous generators. Electrical analysis is becoming one of the major approaches for condition monitoring on wind turbines [20].

New wind turbine fault detection systems compared wind speed to power output obtained from SCADA was presented in [27]. SCADA (supervisory control and data acquisition) is a general name for a computer-controlled system that monitors and controls industrial processes. However, it is difficult to detect incipient faults.

Table 2.1 Summary of typical bearing condition monitoring methods

<table>
<thead>
<tr>
<th>Monitoring Scheme</th>
<th>Major Advantages</th>
<th>Major Disadvantages</th>
</tr>
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<tbody>
<tr>
<td>Vibration Monitoring</td>
<td>Reliable; Standardized (ISO10816) [20]</td>
<td>Expensive;</td>
</tr>
<tr>
<td>Torque</td>
<td>Direct measurement of rotor load</td>
<td>Expensive; Intrusive</td>
</tr>
<tr>
<td>Chemical Analysis</td>
<td>Direct characterization of bearing condition</td>
<td>Limited to bearings with closed-loop oil supply system</td>
</tr>
<tr>
<td>Temperature Monitoring</td>
<td>Standardized (IEEE 841) [20]</td>
<td>Embedded temperature detector required; Insensitive to incipient faults</td>
</tr>
<tr>
<td>Acoustic Emission</td>
<td>Able to detect early-stage fault; Good for low-speed operation High signal-to-noise ratio;</td>
<td>Expensive; Very high sampling rate required; Specialist knowledge required</td>
</tr>
<tr>
<td>Sound Measurement</td>
<td>Easy to measure</td>
<td>Background noise must be shield</td>
</tr>
<tr>
<td>Laser Displacement Measurement</td>
<td>Alternative way to measure bearing vibration; Non-contact measurement</td>
<td>Laser sensor required; Difficult to implement</td>
</tr>
<tr>
<td>Stator Current/Power Monitoring</td>
<td>No additional sensor needed; Inexpensive; Non-intrusive; Easy to implement</td>
<td>Displacement based rather than force based;</td>
</tr>
</tbody>
</table>

Bearing single-point faults were investigated in this research. Table 2.1 [20] summarizes the typical methods for bearing condition monitoring which can be applied to wind turbines of
all sizes. It is clear that these methods have different advantages and disadvantages. Therefore, they should be properly chosen according to the specific applications.

Bearing condition has been popularly and reliably measured via machine vibration. This is because bearing single-point defects will typically produce salient fault signatures in machine vibration [20, 28]. Therefore, vibration monitoring is popular in practice, and well-accepted standards are available such as ISO10816 [20].

Vibration analysis is by far the most popular method for machine condition monitoring because it has a number of advantages compared with the other methods [29]. It reacts immediately to changes and can therefore be used for permanent as well as intermittent monitoring. Intermittent monitoring is not in the scope of this research. Vibration analysis is more likely to point to the actual faulty component. Most importantly, many powerful signal processing techniques can be applied to vibration signals to extract even weak fault indications from noise and other masking signals. Vibration monitoring was selected to detect bearing and rotor imbalance faults of the test rig in the research.

2.4 Test Rig

A dynamic model of a wind turbine generator was developed to simulate three different scenarios including normal operating conditions, blade imbalance and torque asymmetry in [30]. Simplified dynamics models of a DFIG were investigated to obtain a reduced-order model of a wind turbine suitable for transient studies [31, 32]. The stochastic modeling of the vibration signal produced by localized faults in rolling element bearings and its use for diagnosis were investigated in [33].
Signal processing of the various signals is the major and preferable technique for condition monitoring and fault diagnosis on wind turbines. The modeling allows interpretation of the signals and so is complimentary to the measurements. Using a test rig is still essential to develop the condition monitoring and fault diagnosis techniques for various wind turbines. All the papers reviewed so far describe large turbines and their generators. It is important to build the test rig to simulate the small PMG because there is very little available for small turbines. In that context, a test rig is required in which the generator speed can be controlled to develop the techniques that can then be applied to operating wind turbines. Meanwhile, the machine response to isolated faults and varying operating conditions can be studied.

In order to simulate the effects of wind turbines working under different conditions and develop new condition monitoring and fault diagnosis techniques, a wind turbine drive train test rig was built in [25]. The test rig comprises a 50 kW DC variable speed drive controlled motor, a two-stage gearbox with gear ratio 11.14:1 and a three-phase PMG. The power was rectified and then fed to a resistance load bank. In the experiments, the speed of the DC motor was controlled externally so both the properties of the wind and the aerodynamic and mechanical behaviour of turbine rotor were simulated [25]. Both generator electrical and wind turbine mechanical faults were simulated on the test rig. Firstly, a new condition monitoring technique was proposed based on a series of torque-speed experiments. Then, the proposed technique was verified by detecting generator winding and rotor imbalance faults.

Other test rigs with different configurations have been built to investigate the condition monitoring of wind turbines.

A test rig composed of a 7.5 kW DFIG and an AC synchronous machine working as wind turbine emulator. The aerodynamic load was emulated with a synchronous machine according to
the wind profile specified by the computer controlling the rig. [34]. A 50 kW wind turbine, the AOC15/50, which is widely used in Canada and USA, was presented as the target wind turbine to describe condition monitoring instrumentation, data acquisition system and data analysis methodology [35].

All the test rigs described have been successfully used for condition monitoring and fault diagnosis on wind turbines. Since the tip speed ratio is independent of turbine size, the angular velocity of small turbines is much higher than for large turbines, and this may pose additional challenge in signal processing that are not present at large size. For example, 2 MW turbines typically rotate at 16 rpm compared to 500 rpm for the PMG used in this work. Most large wind turbines have condition monitoring but small wind turbines lack this feature due to additional cost involved. No test rigs have been developed for small wind turbines. The test rig to simulate small wind turbines and/or their generators is highly desirable to develop the new condition monitoring and fault diagnosis techniques.

2.5 Signal Processing Techniques

2.5.1 Overview

Signature features can be extracted from the raw data using signal processing techniques once a signal is collected through sensing. The algorithms for signal processing lie within four main categories: time domain, frequency domain, time-frequency distribution and model-based.

The time domain method processes the time series data directly. Common time domain parameters are magnitude, energy, peak-to-peak value, and average. Parameters describing the higher moments of signal distribution have also been used in time domain analysis. Commonly employed are crest factor and kurtosis factor. They are independent of the actual magnitude of
the vibration level and respond more to the spikiness of the vibration signal. As such they provide indication of early stage bearing damage where impulsiveness becomes prominent in the vibration signal. Each time a localised defect in a rolling element bearing makes contact under load with another surface in the bearing, an impulse of vibration is generated. One of the difficulties with crest factor and kurtosis is in their response to increased damage. As the damage worsens, the vibration pattern becomes more random, and as a consequence, the values of crest factor and kurtosis reduce to the undamaged levels, even in various frequency bands [36].

Spectral analysis based on the Fourier transform is the most basic and well-known frequency domain analysis method [36]. Conversion from time domain to frequency domain is through the fast Fourier transform (FFT). Other frequency domain analysis techniques include envelop analysis or modulation analysis by Hilbert transforms, harmonics and sideband detection by cepstrum analysis and others [36].

Traditional frequency analysis techniques such as the FFT are not adequate for non-stationary signals because they assume the signal is stationary [37]. Therefore time-frequency analysis was developed to capture information in both time domain and frequency domain with various time resolution and frequency resolution. STFT is the most commonly used and is generated by windowing the signal in certain short time duration. Its limitations are mainly due to the “uncertainty principle” relating the time and frequency domain. This principle states that the more a signal located in the time domain, the less located in the frequency domain and vice versa [37]. Therefore, to increase the resolution in the frequency domain a longer time sample is required. Inversely, if higher precision in time domain is required then the frequency resolution will suffer. That is the trade-off between time and frequency resolution of STFT. There are other time-frequency analysis techniques such as Wigner-Ville Distribution [38] and Choi-Williams
Distribution [39]. To overcome the trade-off between time and frequency resolution of STFT, Rajagopalan et al. [12] applied other algorithms such as Windowed Fourier Ridges, Born–Jordan distribution and the Zhao–Atlas–Marks distribution [40] to improve the resolution of the time-frequency spectrum. For machines operated with a rapidly changing speed, wavelet analysis is another option to avoid the trade-off between time resolution and frequency resolution caused by the uncertainty principle. Rosero et al. [41] applied both continuous wavelet transform (CWT) and discrete wavelet transform (DWT) to detect demagnetization faults in a generator operating at variable speed.

These frequency analysis based algorithms are relatively time consuming, and it is often hard to determine the source of specific harmonics, so it cannot distinguish faults that have the same signature frequencies, like partial demagnetization, rotor imbalance and imbalanced load [36].

Model-based fault diagnosis has received more attention, from sub-system level to whole system level [3]. Bennouna et al. [42, 43] used model-based approaches for a DFIG to identify faults including winding imbalance and excitation imbalance on either the stator or rotor. The proposed model was extensively verified through experiments on a specially constructed test rig with a 4-pole 30 kW wound-rotor generator, driven by a converter-controlled DC machine.

Parameter estimation can be used for nonlinear fault diagnosis through detecting abnormal behaviour in physical parameters such as current, voltage and speed [3]. A frequency tracking algorithm can be applied to wind turbine condition monitoring signals. The algorithm adapts its time window to the machine speed by calculating the amount of data required for analysis as a function of machine rotational speed such that a fixed number of revolutions are analysed at each stage. The machine speed is assumed constant over a small number of
revolutions. Due to its iterative and frequency localization, the final algorithm is referred to as the iterative localised discrete Fourier transform [44]. A nonlinear fitting order analysis method was used to deal with large fluctuations in the non-stationary signals in [45]. The new method was found to be an effective supplement for traditional order analysis. Recently, empirical mode decomposition (EMD) has proven to be another important alternative and shown great success in dealing with non-stationary, nonlinear signals like those collected from wind turbines [18]. EMD decomposes the signal into a finite number of intrinsic mode functions adaptively without any prior knowledge about the signal, and obtains instantaneous frequency data. Since the decomposition is based on the local characteristic time scale of the data, it can be applied to nonlinear and non-stationary processes.

In the present work, spectrum analysis and wavelet power spectrum were selected to use on fault diagnosis for small PMG running at constant speed. Time-frequency analyses including STFT, CWT and order analysis were used on fault diagnosis for wind turbine running at variable speed.

2.5.2 Bearing Faults

If vibration signatures measured on bearings were simple and clean, detection of bearing flaws would be an easy matter. In practice, however, vibrations measured on a bearing are dominated by high magnitude imbalance and misalignment components and include random vibrations associated with friction and other sources. Imbalance induces vibration at 1X; misalignment shows up at 1X and its harmonics. The spectral components associated with the ringing pulse sequence, which models the resonant response of a highly damped bearing housing as balls roll over a race fault, are not integer harmonics of 1X, and would not be mistaken for them, but are of relatively small amplitude [46]. In a conventional spectrum with a lot of noise,
these components are lost in the spectral noise floor generated by random vibrations and leakage from the higher harmonics [46].

Signals from vibration sensors are usually measured and compared with baseline signals in order to interpret bearing conditions. The methods used to analyze these signals include frequency and time domain analysis. Among the methods use frequency analysis are the bearing defect frequencies analysis method and enveloped spectrum method [36]. Time-domain analysis can use time-series averaging, signal enveloping, kurtosis, and the spike energy methods [36].

To diagnose localized faults in rolling element bearings with a stationary signal, the high frequency resonance technique, also known as envelope analysis, has been widely used as an effective tool for fault diagnosis [46]. Various resonances of the bearing and the surrounding structure will be excited by the impacts caused by localised defects. The excitation will normally be repetitive because the contacts between the defect and the mating surfaces in the bearing are essentially periodic. The frequency of occurrence of the impulses is referred to as the characteristic bearing defect frequencies [15]. It is usual to consider the resonance as being amplitude modulated at the characteristic defect frequency. Envelope analysis provides a mechanism for extracting the periodic excitation or amplitude modulation of the resonance [36].

The essence of envelope analysis is the selection of a high frequency band (relative to the masking components in the low frequency region) and amplitude demodulation in this band to extract the defect frequency. The most common procedure presents a first step of order tracking [47] and synchronous averaging [48], able to remove the undesired components, synchronous with the 1X and harmonics from the signal. A final step of envelope analysis is to obtain the squared envelope spectrum. Sometimes the effect of small speed fluctuations has to be removed in advance, which can be achieved by order tracking.
Unfortunately the first step of synchronous averaging is not sufficient to reject the low-frequency high-amplitude signals associated with imbalance and misalignment and to eliminate noise. An additional step of pre-whitening is needed before the envelope analysis. Pre-whitening helps to equalize the low and high frequency content and enhance the impulsive part of the signal caused by impulse from bearing defect. Different techniques have been proposed and the most used are linear prediction filters and spectral kurtosis (SK). Signals from localised faults in bearings are impulsive, at least at the source, and SK techniques can identify the frequency bands in which this impulsivity is most marked [36]. The SK can be enhanced by "pre-whitening" signal using an autoregressive model. This sometimes reveals an incipient fault at a much earlier stage [49]. Recently, the new technique of cepstrum pre-whitening has been proposed [50].

Bearing defect frequency analysis was used for the generator running at constant speed in the present research.

For small wind turbines, the author is unaware of any use of time-frequency analysis for bearing condition monitoring, or of any implementation of it. STFT, CWT and order analysis method are the methods to be investigated in the research for signal processing on bearing under variable speed.

2.5.3 Imbalance

Imbalance constitutes a significant portion of all faults in wind turbine generators [16]. A common mechanical imbalance in wind turbines is shaft/blade imbalance.

Several signal processing techniques, e.g., the classical FFT analysis, power spectral density (PSD) [51], bicoherence [26], time-frequency analysis [52] and amplitude demodulation [53], have been used for mechanical imbalance detection of wind turbines. The classical FFT analysis, PSD and bicoherence analysis can identify imbalances based on their characteristic
frequencies [54]. However, this is only possible for stationary signals. Time-frequency analysis and amplitude demodulation methods are able to extract fault signatures from non-stationary signals. However, they cannot clearly identify imbalances from interferences that have similar patterns as the faults in the time or frequency domain [53].

Using generator stator current signals for imbalance detection of direct drive wind turbines by power signal analysis was proposed in [24]. Another proposed technique has a versatile function to detect generator electrical or mechanical fault for monitoring the condition of the wind turbine instead of using traditional vibration signals [25].

Spectrum comparison analysis was used for wind turbine running at constant speed in this research. Frequency band energy techniques based on wavelet power spectrum analysis have proven to be a simple and effective way to trending of evolving conditions of mechanical equipment [55] and was used in this research as well. By properly decomposing the signal into various frequency sub-bands, signal energy patterns in these frequency sub-bands can be effectively used on imbalances for machine condition monitoring and fault diagnosis.

For electrical imbalance, no assessments of the need for detecting electrical circuit imbalance or of no implementation of it are recognized for small wind turbines with PMG.

STFT, CWT and order analysis methods were investigated in the present research for signal processing of imbalance for the generator running at variable speed.

2.6 Research Objectives

The objectives of this thesis were to design and build a test rig to simulate a small wind turbine generator. It must be instrumented to collect reliable data to investigate preliminary signal analysis for three common faults including bearing fault, mechanical and electrical
imbalances under constant and variable speed. It is desirable that the rig can be used for further
development of condition monitoring and fault diagnosis techniques on small wind turbine
generators.

The major challenges, which were listed in section 1.2, include:

• The test rig should be set up to simulate a small PMG under variable running speed.
  Meanwhile, it must be capable of allowing the collection and analysis of stationary and
  non-stationary vibration signals and be useable for future research and development.
• It is difficult to select suitable sensors for data collection and choose the best mounting
  location for it.
• It is desired to effectively simulate some faults for the bearing and imbalance.
• Traditional frequency analysis cannot be used with random speed variation. Time-
  frequency signal processing techniques are required to deal with non-stationary signal.
• It is desired to find a method to detect a bearing fault with variable speed.

To overcome the major challenges from the variable speed operation of PMG, the
research methodologies are determined in according with the literature review in this chapter and
were addressed as summarized below:

• A small wind turbine test rig was designed and built, in which a 500 W PMG is driven by
  a standard variable frequency drive (VFD) AC motor.
• Vibration measurement was used for monitoring. Based on a study of sensors and optimal
  locations, an accelerometer was mounted in the load zone of the rear bearing housing.
• Mechanical imbalance was simulated by adding imbalance block on the load disc, which
  locates between PMG and motor.
• Spectrum analysis on the PMG under constant speed was used to show bearing outer race defect characteristic frequency, which is about 3.6 times of shaft rotating speed (3.6X).

• Spectrum comparison analysis and wavelet power spectrum analysis were applied to detect simulated mechanical imbalance, which have defect characteristic frequency 1X.

• Spectrum comparison analysis and wavelet power spectrum analysis were applied to detect simulated electrical imbalance.

• The electrical voltage signals were analyzed to see if they could be used for fault detection.

• Some preliminary analysis using STFT, CWT and order analysis were used to detect the fault of bearing on the variable speed operation of the generator.
Chapter Three: Experimental Setup

3.1 System Concept Design

3.1.1 Concept Formation

Small wind turbines are widely used at rural, residential and remote locations all around the world. In order to maintain maximum efficiency of power extraction, the generator shaft speed changes with wind speed. Speed is normally at the range of 110-660 rpm. The test rig was designed particularly for this application.

Various test rig designs were studied. General mechanical system design principles were followed to build the test rig successfully. Functionality, suitability, strength, reliability, simplicity, flexibility, economic and safety were main considerations in design. Cost effectiveness is also important.

The major challenge for the test rig design was to include speed variation similar to that occurring during turbine operation. Meanwhile, it should allow common faults to be simulated and measurement devices needed be suitable for further analysis.

3.1.2 Test Rig Setup

In order to allow variable speed and develop new condition monitoring and fault diagnosis techniques, a test rig was built as shown in Fig. 3.1 and Fig. 3.2.

The test rig shown in Fig. 3.1 comprises a three phase AC induction motor with variable frequency drive (VFD), driving a permanent-magnet generator (PMG). The PMG has coils on the stator, and permanent magnets on the rotor shown in Fig. 3.3. The three-phase AC output of the PMG is fed to an adjustable resistance load bank. The system was instrumented using LabVIEW, which provides a variety of speed profiles, such as constant speed, sinusoidal and other time varying speeds. Speed, torque, four (4) accelerations and generator voltage, were
measured at the terminals of the VFD and PMG. As illustrated in Fig. 3.1, four accelerometers were used to measure the generator vibration. The voltage was measured for one phase of the generator with a voltage divider. The speed output and torque were read directly from the VFD.

**Figure 3.1** Schematic presentation of the test rig

The general arrangement of main equipment is illustrated in Fig. 3.2.

**Figure 3.2** General arrangement of the test rig
A concrete and steel structure skid foundation design was chosen. The steel skid is mounted to the concrete by two 76.2 mm x 25.4 mm x 558.8 mm mounting plates and main components are mounted on the common skid through flat bars. The PMG was mounted on the special mounting plate on the left hand side. The AC induction motor with VFD control is on the right. One set of flexible coupling was used. The load disc was tightened to an adaptor, which was connected to the PMG by outside thread of the PMG rotor.

Mechanical and electrical imbalances can be studied on the test rig. To create rotor imbalance, a mass block was bolted to the load disc. To create electrical imbalance, one resistor of three phase resistors can be varied.

The test rig was intended as a first step with room for extension as needed for future development of the project. Hence, flexibility was considered. Some extra space was considered in the design. The PMG can be pushed back to accommodate a torque transducer because torque is one of the important mechanical characteristics for the wind turbine system and must be known accurately to determine the generator efficiency. The accuracy of torque value read from the VFD is 5% as per personal communication with vendor. It was not selected in the preliminary analysis for this research. Some electrical current measurement devices can be added for potential electrical current signal analysis, which may complement vibration analysis.

### 3.2 Mechanical Detail Design

#### 3.2.1 Main Equipment Selection

**3.2.1.1 PMG**

It is desirable that the test rig is small in size and power. Design parameters of the PMG were determined as power, $P < 750$ W; $\omega = 100\text{-}550$ rpm. The 500 W GL-PMG-500A PMG shown
in Fig. 3.3 was manufactured by Ginlong Technologies, China (www.ginlong.com). This generator has a maximum operating speed in excess of 600 rpm which is typical for small wind turbine applications. From GL-PMG-500A PMG power curve (see appendix A), the range of power and the range of rotation speed is 0-790 W and 0-550 rpm, respectively.

The features of this PMG are as follows:

- Low start up speed due to low cogging and resistive torque design.
- High standard, quality components for use in harsh and extreme environments for wind turbines.
- High efficiency and low mechanical resistance and energy loss.
- Excellent heat dissipation due to aluminium alloy outer frame and special internal structure.
- High strength from the specially design structure and fully heat treatment aluminium.
- Uses special selected material such as high standard stainless steel shaft, NdFeB (Neodymium Iron Boron) magnet and high standard aluminium alloy with TF/T6 heat treatment outer frame.
- Designed for 20-year operation.
- Patent protected design.

The casing outer diameter is 250 mm. The maximum shaft diameter is 34 mm. The 16 permanent magnets are attached to the rotor and the back bearing is clearly visible in the bottom photograph of Fig. 3.3 [8].

See the specification sheet of GL-PMG-500A in appendix A for details of the mechanical and electrical specifications and some related performance curves.
Figure 3.3 Outside and inside views of the Ginlong 500-A PMG
3.2.1.2 AC Induction Motor with VFD

Motors commonly used in electrical drives are: DC motors, induction AC motors, synchronous motors, brushless DC motors and stepper motors.

Partly due to the presence of commutator and brushes, DC motors have a number of disadvantages as compared to AC motors: higher cost, weight, volume and inertia for the same rating, and need for frequent maintenance. Squirrel-cage induction motors, which cost nearly one-third of a DC motor of the same rating, are extremely rugged, requiring practically no maintenance and can be built for higher torques and power ratings. Because of numerous advantage of AC motors described above, AC drives have replaced DC drives in a number of variable speed applications. Wound field and permanent magnet motors have a higher full load efficiency and power factor than induction motors. Wound field motors can be designed for a higher power rating with higher cost and size than induction motor. Permanent magnet motors have all the advantages of squirrel-cage induction motors except they are available in lower power rating. Brushless DC motors are similar to permanent magnet motors with lower cost and simpler and cheaper converter required. They are used for low power and high speed drives and for servo applications.

From the various test rigs reviewed in section 2.4, both AC induction motor and DC motor were successfully used for the test rig to drive the generator because they can be controlled to emulate the operating conditions of wind turbines. Three phase induction motors are suitable for many purposes and are generally the most economical motor choice, which was selected for the research. Motors that are designed for variable speed operation are often fitted with VFD. AC induction motors with VFD are widely used and are one of the most efficient ways to save energy. In addition, since the ultimate objective is to develop reliable condition
monitoring method for wind turbine operation, accuracy of the motor speed setting is not critical as long as it can be accurately measured.

To size a motor for the application, the entire load range must be considered. Particular attention was paid to the magnitude and length of the peak load. The PMG may range from 20% to 100% of rated power over its operating cycle. Motor size is calculated on the peak load because the motor should be able to drive through the peak demands without overheating. The maximum torque is 18 N-m at 550 rpm from the GL-PMG-500A PMG Input Torque Curve shown in appendix A.

\[ P = \frac{\text{RPM} \times \text{Torque}}{9.5488} = \frac{550 \times 18}{9.5488} = 1.04 \text{ kW} \quad (3.1) \]

From Eq. 3.1, the 1.04 kW is required for the break horsepower of the PMG. Three phases 208 V only is available power in the laboratory. Compared to 230 V motor specifications, power was reduced by around 10%. That means motor will have less ability to drive PMG. Consider the 1.15 safety factor to determine the size of small motor, 1.49 kW motor instead of 1.12 kW was selected. Model PDH00208TE2 Motor was selected. It is 1.49 kW 3 phase 8-pole 230 V rated 850 rpm AC induction motor. See motor mechanical and electrical details from motor technical data sheet in appendix B.

A VFD is a system for controlling the rotational speed or torque of an AC electric motor by controlling the frequency of the electric power supplied to the motor. Many fixed-speed motor load applications that are supplied direct from AC line power can save energy when they are operated at a speed different to that due to mains frequency, by means of VFD. Such energy savings are especially pronounced in variable-torque centrifugal fan and pump applications where the load torque and power vary with the square and cube, respectively, of the speed. This
change gives a large power reduction compared to fixed-speed operation for a relatively small reduction in speed. For example, at 63% speed a motor load consumes only 25% of its full speed power.

VFDs are typically classified by power. However, the size of VFD necessary is probably larger than the size of the motor being controlled by the VFD. This is for two reasons. First, a motor can produce more than its rated power. It is not unusual for a motor to produce up to 15% above the rated shaft power by utilizing the motor’s service factor. Second, the VFD is rated by its output power, which is the input power to the motor. The input power is the motor’s shaft power divided by the motor efficiency.

Model CIMA-AU2A0008FAA was selected. It can be used as a local and remote speed control. AU2A0008FAA 1.5 kW, 230 V, 3 phases and 8 amperes has a computer interference which can be used by LabVIEW. Programmed signal input from the computer provides variable speeds to control the motor. Meanwhile, the VFD collects information from motor and feedback to the computer for regulating the speed and torque.

The VFD has some limitation on the accuracy of the speed output and torque because the motor has no feedback and they are determined by a proprietary algorithm instead of direct measurement from the system. The accuracy of the speed from VFD is 3-5% lower than the accurate speed and see details from Table 3.1.

3.2.1.3 Variable Resistor Load Bank

A 3-phase variable resistance load bank was used. Resistors rated at 3.6 Ω and 14 amperes were selected. Electrical imbalance can be achieved by changing the resistance in one of the phases on the PMG. The resistor can be adjusted manually. It can even be set to zero to simulate shorting of one phase.
Table 3.1 Summary of the speed readout comparisons

<table>
<thead>
<tr>
<th>Speed from VFD (RPM)</th>
<th>PMG Voltage Frequency (Hz)</th>
<th>Speed from PMG Voltage Frequency (RPM)</th>
<th>Speed Ratio Between Voltage with VFD</th>
<th>Speed from FFT of Vibration (Hz)</th>
<th>Speed from FFT of Vibration (RPM)</th>
<th>Speed Ratio Between FFT with VFD</th>
</tr>
</thead>
<tbody>
<tr>
<td>120</td>
<td>16.88</td>
<td>126.6</td>
<td>1.05</td>
<td>2.13</td>
<td>127.5</td>
<td>1.06</td>
</tr>
<tr>
<td>240</td>
<td>33.31</td>
<td>249.8</td>
<td>1.04</td>
<td>4.19</td>
<td>251.3</td>
<td>1.05</td>
</tr>
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<td>49.88</td>
<td>374.1</td>
<td>1.04</td>
<td>6.25</td>
<td>375.0</td>
<td>1.04</td>
</tr>
<tr>
<td>480</td>
<td>66.44</td>
<td>498.3</td>
<td>1.04</td>
<td>8.31</td>
<td>498.8</td>
<td>1.04</td>
</tr>
<tr>
<td>540</td>
<td>74.75</td>
<td>560.6</td>
<td>1.04</td>
<td>9.31</td>
<td>558.8</td>
<td>1.03</td>
</tr>
<tr>
<td>600</td>
<td>83.00</td>
<td>622.5</td>
<td>1.04</td>
<td>10.38</td>
<td>622.5</td>
<td>1.04</td>
</tr>
</tbody>
</table>

3.2.2 Concrete and Skid Foundation

By general industry practice, the weight of concrete should be at least three times the weight of the equipment it supports. Given the weight of the motor and the PMG are 75.7 kg and 14.4 kg respectively, the design weight of concrete should be 270 kg minimum. The concrete was sized as 1,200 mm x 0.660 mm x 0.200 mm (L x W x H) to provide a large amount of margin. The mass density of concrete is around 2,400 kg/m³, so the weight of the slab was 380 kg. In addition, there is a small amount of torque passed onto the concrete from the PMG and AC motor.

Considering the weight and portability, a single slab was designed for the test rig. Two 3” x 1” x 22” flat bars were supported by two pieces of 2” x 2” x 2” angle steel at each end of it. These located the flat bars on top of the concrete precisely during pouring the concrete. Four 3/8”-16 threaded holes are used to connect the steel skid to the slab. See test rig structure assembly, base assembly and flat bar details in appendix C1, C2 and C3.
The skid was designed to be 1067 mm x 406 mm x 76 mm and comprised 6 pieces of 4” x 1 5/8” channel steel, which were welded to form a common base as detailed in appendix C4. The PMG sat on two flat bars 3” x ½” x 17” and was bolted by four sets of 3/8” bolts. The AC motor sat on two flat bars 3” x ½” x 17 ½” and was bolted by four sets of 3/8” bolts. See details of the PMG supporting flat bar and motor supporting flat bar in appendix C5 and C6. Considering the elevation of the PMG and AC motor, four shims for the AC motor were used with 1 ½” x 1 ½” x 1/8” x 1” hollow steel structure (HSS) to bring equipment alignment properly.

3.2.3 Ancillary Equipment

3.2.3.1 Mounting Plate for PMG

The designed mounting plate of PMG comprises two plates, which were welded together vertically. The size of the horizontal piece is ½” x 4” x 11”; and the size of the vertical piece is ½” x 10 ½” x 11 ½”. The rear of the PMG was mounted onto vertical part of the mounting plate. The horizontal part of the mounting plate was then mounted to the skid. See details dimensions as per drawing for the mounting plate in appendix C7 and C8.

Five 3/8” holes were drilled in the vertical plate to align with the mounting bolts for PMG. Also four 7/8” holes were drilled. One is for three electrical power cables and another one is for cables of the accelerometers mounted inside the PMG cover. For the horizontal plate, four holes were designed for mounting bolts to hold it to the skid.

One innovative mechanical design was that two side webs, made with precise dimensions, keep the two mounting plates vertical to each other. It is impossible for two plates to be positioned vertically to each other without any webs due to the distortions during welding. It
is traditional that webs are placed between plates to increase the strength, which would still be very hard to get perfectly vertical.

3.2.3.2 Load Disc

A circular load disc was designed to allow simulation of the mechanical imbalance for the research. See details for the load disc drawings in appendix C9. To produce mechanical imbalances, different mass blocks were bolted to the load disc. The load disc was bolted onto an adapter, which had one end threaded into the end of PMG shaft and the other end into a flexible coupling to connect with the AC motor.

Aluminum was used for load disc to reduce the overhang weight. Four ¼” threaded holes were arranged evenly over the load disc and are placed as far as possible from the centreline of the load disc to maximize the mechanical imbalance.

3.2.3.3 Other Components

High quality NSK 6207DDUC3 (Front) and NSK C (Rear) bearings are used in the PMG. The rear bearing NSK 6207C, which can be seen in Figure 3.2, to be mounted away from the motor, was used for vibration analysis because it carries higher loads. It was interference fit into the bearing housing. Bearings 6306ZZ and 6308ZZ were used in the AC motor.

A LOVEJOY flexible coupling L-100X1-3/8STD5/16 x 5/32 kW hub with L/AL099/100 sox spider was sized to connect the PMG with the AC motor.

To protect the experimenter, a coupling guard covered the space between the PMG with AC motor. The guard was made from steel mesh bent into shape. Four holes were drilled to bolt onto the skid.

Three Fuses are installed into the all three resistor loop to protect against excessive electrical current.
Warm grey color was chosen for the painting. There are no painting underneath the machine feet and mounting plate to avoid the cushion effect from the painting.

3.2.4 Safety Considerations

The following safety measures were used to make the test rig safe to operate:

- Coupling guard was used at all times during operation;
- Safety guard was placed over the resistors to avoid burning;
- Safety fuse for each electrical loop was placed to avoid PMG overheating;
- Electrical cable connectors were used for electrical and instrumentation cables to provide a safe and functional connection for years to come;
- Very conservative mounting was used to secure the accelerometers inside PMG;
- Vibration isolation pads were placed under the concrete to isolate the test rig from the building.

3.3 Instrumentation

3.3.1 Accelerometer

Vibration analysis was determined to be the major methodology for the research. Firstly, vibration analysis is the most well known method in industry and the baseline created can be used to compare for future condition monitoring and fault diagnosis. Also the effective methodology developed from vibration analysis of a small generator potentially can be applied to larger ones for wind energy and other industry.

3.3.1.1 Selection of Sensors

Traditional vibration sensors fall into three main classes: noncontact displacement transducers, velocity transducers and accelerometers. By far the most commonly used are
accelerometers [56]. These devices contain one or more piezoelectric crystal elements, which produce voltage when stressed in tension, compression or shear. This is the piezoelectric effect. The voltage generated across the crystal pole faces is proportional to the applied force. Accelerometers have a linear response over a wide frequency range (0.5 Hz to 20 kHz). This wide linear frequency range and the broad dynamic amplitude range make accelerometer extremely versatile sensors.

Noncontact displacement transducers are limited in temperature and frequency response. Velocity transducers have strong signal, however they are heavy and large in size and have less accuracy in higher frequency range [56]. A piezoelectric single-axis accelerometer was selected due to their wide frequency range and suitability for limited space inside PMG, lightweight, good temperature resistance and moderate price.

3.3.1.2 Accelerometer Details

Four ISOTRON accelerometers (ENDEVCO) M50 with ISOTRON signal conditioner M4475 were selected for this research.

Accelerometer type: Model 50; sensitivity: 50 mV/g; range: ±40 g; resonant frequency: 10 kHz; frequency response: 2~4000 Hz for ± 5% amplitude response. Signal conditioner type: Model 4475(ENDEVCO); channel number: 10 channel.

The ENDEVCO® Model 50 is a small piezoelectric accelerometer with integral amplifier, developed specifically for modal measurements or OEM vibration applications. In addition to having minimum unit-to-unit phase deviations, the built-in microcircuit has been configured to work in a constant current mode with a supply voltage as low as +12 VDC. The units are designed to be mounted with adhesive. A dielectric layer on the base isolates the case ground from the mounting surface to eliminate potential ground loops. This accelerometer is
hermetically sealed to provide long-term reliability even in harsh environments, and their light weight (3.8 gm) effectively minimizes mass loading effects.

For convenience, the Model 50 come with a 3-meter pair of output wires attached, ready to be used right out of the box. A matching low-cost, 10-channel power supply (Model 4475) is supplied together.

The signal conditioner provides the power supply; and also functions as an amplifier for the acceleration signal.

See sensitivity, range and other details of accelerometer M50 from the specification in appendix D.

3.3.1.3 Mounting Location and Method

Accelerometers are sensitive to mounting and torque and may generate too much noise. A key factor in being able to accurately detect and diagnose rolling-element bearing defects is the placement of the vibration sensor. Because of the relatively high frequency involved, accelerometers should be placed on the bearing housing as close as possible to, or within, the load zone of the stationary outer race.

![PMG Cover](image)

**Figure 3.4** Accelerometer mounting locations on the rear PMG housing
The four accelerometers were placed as shown in Fig. 3.4. The results showed that the best location was location 3, which is immediately below the bearing housing. This is intuitively correct because this location is nearest to the bearing load zone which generates the highest signal power. The bearing housing is away from the outside cover of the PMG. Vibration signals collected at location 2 and 4 appeared random, with no obvious bearing defect signature.

Installation of accelerometers requires a rigid mounting. Permanent installation with studs or bolts is usually the best where high-frequency measurements are required. The close coupling between the machine and the sensor allows for direct transmission of the vibration to the sensor. This type of mounting is not practical for the test rig due to space limitation inside the PMG. Furthermore, the vibration levels were too low to dislodge the accelerometer even if it were less securely mounted.

Adhesive is a simple and effective means of mounting vibration transducers with limited high-frequency sensitivity (4 to 5 kHz). Wax was used to mount the 4 accelerometers. Small flat surfaces were milled at mounting location 1 and 3 in Fig. 3.4. Extra electric tape was wrapped around the outside rim of the bearing housing. For more security, a pipe clamp was used to fasten the accelerometers.

3.3.2 Voltage Divider

A voltage divider is a simple circuit which turns a large voltage into a smaller one suitable for data acquisition. Using just two resistors in tandem, an output voltage that is a fraction of the input can be created and measured using the Ohm’s law. Two 4 kΩ and 6 kΩ resistors were connected in series and then used to connect in parallel with the one phase of the PMG power output. The voltage can be directly measured out by instrumentation, which are less than 10 V. The current was not significantly altered by the voltage divider.
3.4 Data Acquisition (DAQ) System and Signal Processing

3.4.1 DAQ System

3.4.1.1 General

Data acquisition has always been at the heart of every vibration application. LabVIEW was used to run the DAQ system. It is commonly used as a development environment with build-in functionality for simulation, data acquisition, instrument control, measurement analysis, and data presentation.

To perform condition monitoring, sensor and data acquisition equipment for continuous measurements is required. In the experiments, the speed of the AC induction motor is controlled by the VFD under LabVIEW, to allow mimicking of the variation in natural wind and the mechanical behaviour of turbine rotor. In these initial experiments, a variety of speed inputs such as constant speed, sine wave and other continuously varying speed were applied. All relevant signals such as speed output, torque, four accelerations and voltage were collected using LabVIEW.

At its most basic level, the task of a DAQ system is the measurement of physical signals. A DAQ system generally has signal conditioning, plug-in DAQ board, software for acquiring and manipulating the raw data, analyzing sensors and transducers, and a suite of software for analyzing and displaying (and storing) data.

In many cases, the measured signal has a very low-voltage and is susceptible to noise. Therefore, it is common that the measured signal be amplified and filtered before being digitized for further processing in the computer. The four acceleration measurements were connected to the signal conditioner for amplification to achieve a voltage range of -10~+10 V.
3.4.1.2 Components of the DAQ System

The main components of the DAQ system are as follows:

(1) SCXI Terminal Block

Type: NI SCXI-1302, which is 50-screw terminal block for the SCXI-1000 feed through panel. SCXI terminal blocks provide a convenient method for connecting and disconnecting signals to the system. The NI SCXI-1302 front-mount terminal blocks feature direct connections to transducers at the screw terminals located within a fully shielded enclosure or at front-mounted BNC connectors. Strain-relief clamps hold the signal wires safely in place.

(2) DAQ Card

Type: NI PCI-6024E, which is 68-pin E series line; 16 analog inputs; sampling rate: 200kS/s; resolution: 12 bits.

The DAQ hardware acts as the interface between a computer and signals from the experiment. It digitizes incoming analog signals so that a computer can interpret them. The three key components of a DAQ device used for measuring a signal are the signal conditioning circuitry, analog-to-digital converter (ADC), and computer bus. The DAQ devices include other functions for automating measurement systems and processes. For example, digital-to-analog converters (DACs) output analog signals, digital I/O lines input and output digital signals, and counter/timers count and generate digital pulses.

Signals from sensors or the outside world can be noisy to be measured directly. Signal conditioning circuitry manipulates a signal into a form that is suitable for input into an ADC. This circuitry can include amplification, attenuation, filtering, and isolation.

An ADC is a chip that provides a digital representation of an analog signal at an instant in time. In practice, analog signals continuously vary over time and an ADC takes periodic
“samples” of the signal at a predefined rate. These samples are transferred to a computer over a computer bus where the original signal is reconstructed from the samples in software.

DAQ devices connect to a computer through a slot or port. The computer bus serves as the communication interface between the DAQ device and computer for passing instructions and measured data. DAQ devices are offered on the most common computer buses including USB, PCI, PCI Express, and Ethernet.

All the measured signals are analog signals, which are acquired simultaneously. After they are transformed into -10–10 V digital signals, they are acquired by the NI data acquisition device, including 50-pin SCXI-1302 terminal block connector and PCI-6024E I/O assembly. NI SCXI cable assemblies connect the DAQ to the SCXI system. Each SCXI cable assembly includes a cable and one or more SCXI cable adapters. The shielded cables use twisted pairing and separately shield analog and digital signals for maximum noise rejection. The cable adapter screws into a rear slot of the SCXI chassis to hold the cable securely in place. Each cable adapter also has a 50-pin male breakout connector, for attaching additional DAQ accessories such as the SCXI-1000 feedthrough panel.

3.4.1.3 DAQ Hardware Configuration

Virtual instruments (VI) are the building blocks of LabVIEW programming. VIs have three main components: the front panel, the block diagram, and the icon and connector pair. The front panel is the interactive user interface of a VI – a window through which user interacts with the code. The block diagram is the source code for the VI. The source code is “written” in the G programming language and is made up of graphical icons, wires, and such, rather than traditional “lines of code”. The block diagram is actually the executable code. The icons and connectors specify the pathways for data to flow into and out of VIs. An important element of LabVIEW is
the so-called Express VI. These VIs are provided to allow quick construction of VIs designed to accomplish common measurement tasks, such as data acquisition.

DAQ Assistant Express VI was used to configure the measurement tasks and channels. The procedure is as follows: creating a new virtual configuration, selecting the measurement type and creating a new local channel, naming the task and finishing the task configuration. See configuration details in the configuration Fig. 3.5.

![Figure 3.5 Accelerometer DAQ setup](image)
3.4.2 Software Function and Implement

3.4.2.1 General

LabVIEW functions include generating the signal to control the motor speed, collecting the signal from each sensor, signal preprocessing, time-wave figure, data storing, and spectrum analysis of vibration data.

3.4.2.2 Speed Control

The Simulate Signal Express VI is the centre element on the block diagram in Fig. 3.6. The front panel is shown in Fig 3.7.

![Figure 3.6 Block diagram of the sine wave speed input](image)

The Simulate Signal Block simulated various input functions, which control the motor speed through VFD for the test rig. Sine waves, square wave, triangular waves, saw-tooth waves and noise signal can be created by this VI as well. The remaining elements in the block diagram permit easy access to key parameters of the sine signal: magnitude, offset and frequency.
The offset value represents the mean value of the sine signal. Constant speed control can be achieved by setting the magnitude to zero from the sine waves.

![Figure 3.7 Front Panel of the sine wave speed input](image)

The continuous varying speed control was simulated and the block diagram is also shown in Fig. 3.8.
Figure 3.8 Block diagram of the continuous varying speed input
3.4.2.3 Signal Processing

Data were collected through LabVIEW and then processed by digital signal processing (DSP) by MATLAB. The DSP from LabVIEW was used for preliminary analysis and verified by MATLAB.

A common practical algorithm for transforming sampled signals from the time domain into the frequency domain is known as the discrete Fourier transform (DFT) which is a practical example of a FFT.

According to the Shannon Sampling Theorem, it is possible to completely reconstruct a continuous-time signal from discrete, equally spaced samples if the highest frequency in the time signal is less than half the sampling frequency. This is called the Nyquist frequency.

The one main purpose of filters is to remove unwanted noise from a signal. Band pass, with range 1-1024 Hz, infinite impulse response (IIR) filter implementing an order 9 Butterworth filter, was used to achieve reasonably good results.

In most situations, chopping a continuous signal by a square or other type of window can lead to a phenomenon known as spectral leakage. Leakage is that spectral energy in a specific range leaking into other frequency regions [57]. The defect characteristic frequency might not be recognizable if leakage creates a mask for the vibration analysis. A remedy to the problem of spectral leakage is the windowing technique. Hanning windows were used for smoothing to reduce the amplitude of the discontinuities at the boundaries of the accelerometer signals.
Figure 3.9 Block diagram of the developed VI

Figure 3.10 Front panel of the developed VI
The block diagram and front panel of the developed LabVIEW program are illustrated in Fig. 3.9 and Fig. 3.10 respectively.

The front panel displays the rotational speed, acceleration, voltage, and torque with time. The fast Fourier transform (FFT) of generator vibrations is displayed on it as well. Spectral Measurement Express VI was designed and placed in the block diagram. As illustrated in Fig. 3.9, once the Spectral Measurement Express VI was placed in the block diagram, a dialog box automatically appears to configure the VI. The power spectral density was chosen from the options include choosing the measurement type, such as magnitude (peak or root mean square (RMS)), power spectrum and power spectral density, and then selecting the Hanning windowing from the windows among Hanning, Hamming, Blackman-Harris, and Low Side-lobes.
Chapter Four: Preliminary Vibration Analysis under Constant Speed

4.1 Introduction

Data acquisition has always been at the heart of every vibration application. However, it is not enough to just simply collect data. The raw information has to be analyzed, processed, and interpreted into meaningful contents.

Based on vibration and machinery dynamics, complete rotor dynamics models are often very complicated and sometimes impossible to determine because of the complexity of equipment and uncertain propagation paths. The transmission path from signal source to sensor location is usually very complex. It may involve multiple propagation paths, frequency-dependent speed of propagation, attenuation and multiple sources.

Digital signal processing (DSP) in vibration analysis is much preferred method for condition monitoring and fault diagnosis. DSP is the mathematical manipulation of a digital signal to modify or improve it in some way. It is characterized by the representation of discrete time, discrete frequency, or other discrete domain signals by a sequence of numbers or symbols and the processing of these signals. In DSP, digital signals are usually studied in one of the following domains: time domain (one-dimensional signals), spatial domain (multidimensional signals), frequency domain, and wavelet domain. The choice of domain in which to process a signal is sometimes an informed guess (or by trying different possibilities) as to which domain best represents the essential characteristics of the signal. A sequence of samples from a measuring device produces a time or spatial domain representation, whereas a discrete Fourier transform produces the frequency domain information [58].

Vibration signals contain very rich information about machine operating and health conditions. It is important to understand different vibration signatures embedded in the signal
and to properly extract them. Time domain parameters are useful in detecting defects but they can't always be used to indicate the defect's location. Conventionally, diagnosis of component defects and detecting the presence of periodic components in a signal has been done by analyzing the spectrum of the signal if the machine is running at constant speed. Distinctive peaks can be observed in the frequency spectrum. The peaks of the defective components also can be observed compared to that of the good ones due to defect-induced impulses or to prior spectra taken from the machine before the fault developed. Relating other time domain signal characteristics (shape, magnitude, etc.) to mechanical integrity is often much more difficult, and frequency analysis is useful to pinpoint problem with time domain signal characteristics together.

Fourier series decomposes periodic signals into weighted sines and cosines. Signals other than periodic can also be expressed as a sum of complex exponentials to which the so-called Fourier transform applies. The Fourier transform can be derived from the Fourier series by allowing the periodic time to tend to infinity. The Fourier transform converts a time domain representation of a signal into a frequency domain representation. The discrete Fourier transform (DFT) is commonly used due to the use of digital computers for signal analysis. The fast Fourier transform (FFT) is an optimized implementation of a DFT that takes fewer computations and less time to perform [58].

Despite its common use, there are many downfalls to the sole application of frequency analysis because its results, such as a power spectrum or total harmonic distortion, contain only the frequency information of the signal. They do not contain time information. This means that frequency analysis is not suitable for signals whose frequencies vary over time.

The second limitation of the FFT is that it cannot detect transients or short spikes in the signal. Transients are sudden events that last for a short time in a signal and usually have low
energy and a wide frequency band. When transients are transformed into the frequency domain, their energy is spread over a wide range of frequencies. Since transients have low energy, their existence is not obvious in the frequency domain.

Vibration-based diagnostics is often applied to rotating equipment. Specific signal characteristics can be correlated to specific machine components. The term "signature" is often used to describe signals measured on machines and their elements, which can be indicative of their health condition. Decomposing such signals can reveal components with frequencies in relation to the basic rotational speed, and hence carry information concerning the status of rotors, bearings, gears, couplings, blades, etc.

Frequencies that match the machine or shaft rpm are denoted as 1X. There may be vibrations at a frequency that is a direct multiple of the rotating speed of the machine. These can be 1 x rpm, 2 x rpm, 3 x rpm, or even ½ x rpm. These vibrations are said to be locked in with the rotating speed of the machine.

Finding the part of the rotating machine causing the vibration is accomplished by the analysis of the frequency and amplitude readings collected during the monitoring. The frequencies of vibration are normally at low shaft orders for imbalance, misalignment, bent shaft, cracked shaft. The characteristic frequencies of a single-point fault in vibration measurements depend on the bearing geometry and rotating frequency. The configuration of a ball bearing and the theoretical fundamental characteristic frequencies of the four types of single-point faults in vibration measurements can be found in [15]. Determining the problem with the part is the next step, and to accomplish this, the characteristics of vibration for each type need to be known [17].
4.2 Mechanical and Electrical Faults

Common faults are mechanical imbalance, misalignment, shaft bending, mechanical looseness, bearing and electrical defects. Section 4.2.1 discusses the characteristic frequency of the bearing fault. The mechanical and electrical imbalances are simulated in this research due to their widespread occurrence and importance.

4.2.1 Bearing Fault

4.2.1.1 Background

Bearings are essential components of most rotating machinery. The majority of the problems in rotating machines are caused by faulty bearings. Improving the reliability of bearing fault detection and diagnostics will reduce catastrophic damage to equipment. The majority of electrical machines use ball or roller bearings which commonly fail. These bearings consist of an inner and outer race ring with a set of balls or rolling elements placed in races rotating inside these rings. Faults in the inner race, outer race or rolling elements will produce unique frequency components in the measured machine vibration and other sensor signals. These bearing fault frequencies are functions of the bearing geometry and the running speed.

4.2.1.2 Bearing Kinematics

An understanding of bearing geometry and kinematics is essential for bearing fault detection as it determines the contact occurrence between two mating elements, proving bearing defect characteristic frequencies.

A number of articles deal with bearing geometry and kinematics [15, 28, 59]. Fig. 4.1 [28] shows a schematic of a typical ball bearing in the general case with rotating inner race and stationary outer race.
The ball bearing frequencies, for rotating inner race and stationary outer race, are [15, 28]:

\[ f_c = \frac{f_r (1 - \frac{D_b \cos(\theta)}{D_c})}{2} \]  \hspace{1cm} (4.1)

\[ f_{bpfl} = \frac{Zf_r (1 + \frac{D_b \cos(\theta)}{D_c})}{2} \]  \hspace{1cm} (4.2)

\[ f_{bpfo} = \frac{Zf_r (1 - \frac{D_b \cos(\theta)}{D_c})}{2} \]  \hspace{1cm} (4.3)

\[ f_{bsf} = \frac{f_r D_c}{2 D_b} \left( 1 - \left( \frac{D_b}{D_c} \cos(\theta) \right)^2 \right) \]  \hspace{1cm} (4.4)

Equations (4.1)-(4.4) are the general forms of the bearing defect frequency equations assuming no slip and with stationary outer race [59]. In practice, slip will almost always be present, and theoretical expected frequencies will be slightly different [59].
4.2.1.3 Bearing Fault

Bearing failures can be caused by a large number of factors, of which corrosion is one of the most common. Corrosion occurs when water or other contaminants enter bearing assembly. This can be caused by damaged bearing seals, acidic lubricants or condensation. The result is rust on the running surfaces. The rust particles also have an abrasive effect which generates wear. The rust pits often form the initiation sites for subsequent flaking and spalling [60].

In the early stage of this research, acid was to be used on the bearing race to simulate a corrosion defect. A single-point defect of the inner race was considered as the first step to simulate the bearing defects. However, a peak was observed from the spectrum analysis at the bearing outer race characteristic frequency when the baseline spectrum was determined. The plan was changed to keep using the existing bearing and PMG to carry on the research for the signal analysis. Some small scratches were left on the bearing outer race shown in the photographs shown Fig. 4.2 which were taken after the present experiments were completed.

Figure 4.2 Outer race of the bearing
4.2.2 Imbalance

Imbalance causes excitation by forces rotating at the shaft speed when the centre of mass is not at the centre of rotation. The response depends on whether the inertias on the shaft are localized or distributed axially, and whether the shaft is running below or above its first critical speed. If the shaft is short and the inertia localized such as wind turbine rotors, there will be a radial force rotating at shaft speed, which acts as a periodic excitation force in the radial direction, with frequency equal to 1X. This force is minimized by mass balancing, where mass removal (or addition) results in a cancelling force component. The vibration resulting from mass imbalance thus has the form

\[ x(t) = A \sin(2\pi f_r t + \varphi) \]  

where \( x(t) \) represents the vibration signal, \( A \) is its amplitude, and \( \varphi \) phase angle depending on the reference point at initial time.

For electrical imbalance, the variation in currents of the three phases disturbs the magnetic field distribution within the motor which produces a net magnetic force on the rotor. This unbalanced magnetic field can cause mechanical vibration. No research was found in this area for a small PMG.

A rotor imbalance was simulated by attaching a mass block to the load disc. Electrical imbalance was simulated by making one of the resistances in the load bank lower than the other two.
4.3 Spectrum Analysis

4.3.1 Introduction

MATLAB was used for the DSP in this research due to the flexibility, strong computation and graphics ability. MATLAB Program flowchart is illustrated in Fig. 4.3. Each component is discussed briefly in the following paragraphs.

De-trend: Any trends in the data must be removed prior to computation of the spectrum because error terms owing to the trend in the data may produce large errors in the estimated spectrum. De-trending removes the mean value or linear trend from a vector or matrix before FFT processing.

Filter: Applying a predetermined weighing to different regions. Typical applications are the separation of signal components, which are concentrated in different frequency regions, and the improvement of signal to noise ratio be the rejection of undesired components.

Windowing: The original signal is not time limited. For reasons of practicality, DSP processes a time-limited version, so some truncations must be performed. This truncation leads to “spectral leakage”, which occurs when the energy from the signal (caused by discontinuities in the measurement) shows up at incorrect frequency. The result is that energy at a single frequency is spread over adjacent frequencies, hence the term “leak” and high side lobes seen in the un-windowed spectrum plot. Windowing is a technique used to shape the time portion of the measurement data, to minimize edge effects that result in spectral leakage in the FFT spectrum.
Harris [61] has considered in detail the effects of the different window characteristics on window performance and concluded that the major influences on window quality are the highest side lobe and worst-case processing loss. Tukey, Hanning, and Hamming windows are widely used.

Algorithm: FFT, Burg, Welch and others

Display: 2D and 3D graph with user defined axis, title, unit, legend and text box.

A MATLAB script based on the above flow diagram Fig. 4.3 was written. The program was used on a combined sine wave signal to validate its suitability. A common use of Fourier transforms is to find the frequency components of a signal buried in a noisy time domain signal. Consider data sampled at 1000 Hz. A signal

\[ x(t) = 0.5 \sin(2\pi \times 50t) + 2 \sin(2\pi \times 120t) + 2 \ast \text{randn}(\text{size}(t)) \]  

(4.6)

contains a 50 Hz sinusoid of amplitude 0.5 and 120 Hz sinusoid of amplitude 2 and corrupted by a zero-mean random noise with standard deviation 2 shown in Fig. 4.4.

![Figure 4.4 Time waveform of Eq. (4.6)](image)

56
It is difficult to identify the frequency components from the original signal. The discrete Fourier transform of the noisy signal is shown in Fig. 4.5. There are two peaks at frequency 50 Hz and 120 Hz in spectrum, which match the frequencies of the deterministic terms in Eq. (4.6).

![Figure 4.5 Spectrum of the signal corrupted with zero-mean random noise for 1000 samples](image)

**Figure 4.5** Spectrum of the signal corrupted with zero-mean random noise for 1000 samples

The main reason the amplitudes are not exactly 0.5 and 2 is noise. Repeated executions of this code will produce different approximations to these amplitudes. The other reason is that a finite length signal is used. Increasing sample number from 1000 to 10000 in the example above will produce much better approximations on average.

The use of the FFT for frequency analysis involves two important relationships [37].

1. The first relationship links the highest frequency that can be analyzed \( (F_{max}) \) to the sampling frequency \( (f_s) \) as per Nyquist theorem.

\[
F_{max} = \frac{f_s}{2}
\]  

(4.7)
2. The second relationship links the frequency resolution ($\Delta f$) to the total acquisition time, which is related to the sampling frequency ($f_s$) and the number of samples in the FFT (N).

$$\Delta f = \frac{f_s}{N} \quad (4.8)$$

Accuracy of the spectral analysis is addressed in [37] according to different error mechanisms. Three major types of errors encountered in the spectral analysis are leakage errors, bias errors and random errors. Leakage transfers computed spectral power into frequencies that are absent from the physical signal. Bias errors are systematic errors, over- or under-estimating the correct results. They are often caused by transducer calibration errors which are not important in the present work. Random errors cause an uncertainty in the results, to be quantified by statistical parameters. The variance or standard deviation of this error can be used to define an uncertainty gap around the computed results.

These errors can be controlled by appropriate tools. Leakage is controlled by windowing the data. Bias errors caused by insufficient frequency resolution can be controlled by choosing sufficiently long signal duration. Increasing the number of data points available often reduces the random error [37].

4.3.2 Spectrum Analysis

Equation (4.3) can be used to calculate bearing outer race characteristic frequency. Based on the data sheet of the bearing NSK 6207 C used in the experiments, $Z$ (the number of rolling elements) is 9; $D_b$ (Ball diameter) is 11 mm; $D_c$ (pitch diameter) is 53.5 mm; contact angle $\theta$ is $0^\circ$ and can be varied slightly. So the calculated frequency is $3.6f_r$ according to Eq. (4.3).
The data collected from the test rig was entered to the MATLAB program. The program parameter settings are as following:

- Sampling rate: 256 Hz;
- Filter: low pass order 9 Butterworth filter with cut-off frequency 128 Hz;
- Window: Hanning;
- Algorithm: FFT.

For $f_r = 9$ Hz, the FFT spectrum is shown in Fig. 4.6:

![Single-Sided Amplitude Spectrum of y(t)](image)

The two significant peaks at frequencies 3.6X and X were shown on the spectrum. The first peak clearly matched with the bearing outer race defect characteristic frequency 3.6X. The second peak occurred at 1X, which has additional contributions from the imbalance, misalignment and other sources.
4.3.3 Validation

4.3.3.1 Mounting Locations for Accelerometer

Accelerometers were placed at four different locations as shown in Fig. 4.3. Location 1 is at 3 o’clock outside of the bearing housing. Location 2 is at 3 o’clock outside of the PMG cover. Location 3 is at 6 o’clock outside of the bearing housing. Location 4 is at 6 o’clock outside of the PMG cover.

For a constant shaft rotating speed at 9 Hz, the spectrum comparison for the four different mounting locations is shown in Fig. 4.7:

![Spectrum comparisons for the different mounting locations](image)

**Figure 4.7** Spectrum comparisons for the different mounting location

The results verify that the best location was location 3, which is immediately below the bearing housing. The signal power is the largest at this location, which makes intuitive sense because this is inside the load zone. The bearing housing is away from the outside cover of the PMG. The vibration signals collected at the location 2 and 4 are not as good for the obvious reason of transmission path and without any obvious bearing defect signature.
Comparing to the signal collected inside the cover, the signal collected from the outside of the generator is random and did not pick up any machinery fault such as bearing, presumably due to damping of the cover and holding force from the five bolts that can be seen in Fig. 3.2.

4.3.3.2 Skid Foundation

Eleven measurements of acceleration were collected while the accelerometer was evenly placed on different location of the skid foundation.

Figure 4.8 Spectrums to validate the foundation (top: full view; bottom: zoom in view)

Comparing to the signal collected inside of cover, the eleven signals collected on the skid were random and did not pick up any machinery fault such as bearing defect and mechanical imbalance, which is shown in Fig. 4.8. Also, the magnitudes approximately at 0.0158 g are much less than the ones 0.940 g and 0.1166 g collected at location 3 for the frequencies at 3.6X and X.
So the signal collected from bearing housing represents the component faults of the PMG rear bearing. It means that foundation is strong enough can be considered still during system operation. The acceleration signals collected are appropriate for further signal processing to monitor the machinery.

4.3.3.3 Speed Correction

There are three methods used in the research to get the speed readings: directly read out from VFD, read out from spectrum analysis and calculate from the voltage analysis.

Speed readout from VFD, based on an unknown algorithm, is not the exact shaft speed because there is no feedback loop inside the motor. Also another problem is that induction motors have slip which cannot easily determined.

Spectrum analysis of the PMG output voltage can be used to get the shaft speed reading when nothing better is available because there is always a peak at shaft rotating speed 1X. Then the speed reading can be measured with a resolution dependent on the frequency resolution which is a function of the sampling rate and sample numbers. The following formula can be used to calculate the shaft speed.

\[
fr = \frac{120 \times F}{p} \quad (4.9)
\]

where \( F \) is power line frequency in Hz; \( p \) is number of PMG poles, which are 16 for GL-PMG-500A. For \( fr = 540 \) rpm, the voltage was collected from one phase of PMG, which was shown on the fundamental speed peak in Fig. 4.9.
Figure 4.9 Spectrum of the voltage signal

Figure 4.9 showed that the actually power line frequency is 74.75 Hz. So the shaft rotating speed calculated from Eq. (4.9) is 560.6 rpm.

More data sets were collected at different shaft rotating speeds and shown in Table 3.1 for comparison. Results are summarized as:

- The speed reading directly from the VFD is not accurate and needs correction to achieve better accuracy.
- Speed correction factor is about 1.04 from FFT and voltage analysis.
- Some adjustments for speed correction factor are required for speed at 120 rpm, 240 rpm and 540 rpm, which are slightly different with 1.04 from FFT and voltage analysis.
- The speed readings from VFD, which are lower than $f_r$ by around 4-5%, do not affect the result of the preliminary vibration analysis in the thesis. It is only the ratio between the fault frequency and the shaft rotating frequency that is important to fault diagnosis. The absolute value of the shaft speed is not critical.
4.3.4 Waterfall Baseline

It is important to take initial vibration signatures of a machine upon installation to give a baseline for future analysis. When faults begin to develop, the dynamic processes in the machine change and some of the forces acting on machine also change, thereby influencing the vibration level and the shape of the vibration spectrum.

The severity of a vibration can be determined by comparing with the baseline.

![Waterfall baseline using FFT](image)

**Figure 4.10** Waterfall baseline on vibration measurement on nominal $f_{rv}$ from VFD

Figure 4.10 was generated from VFD speed reading ranges from 110 rpm to 600 rpm with 10 rpm interval. Some results from the baseline are summarized below:

1) The first significant peak clearly matched with the bearing outer race defect characteristic frequency 3.6X at all speeds;

2) The second significant peak occurred at 1X, which is nearly always apparent in the spectrum mostly due to imbalance, misalignment and bent shaft at all speeds;

3) The magnitude can serve as a reference for future analysis.

4) The magnitude increases with increasing speed in most cases.

5) The magnitudes do not always follow this speed trend as there is a decrease with the speed increasing in some regions around 420 rpm and below 120 rpm.
4.4 Spectrum Comparison

Spectrum comparison analysis has been investigated for the purpose of bearing signature analysis [17]. A baseline spectrum is taken when the machine is in good condition. The difference between the baseline and subsequent signal spectrum is used to highlight changes in mechanical condition. The comparison is used to locate those frequencies in which significant increases in magnitude have occurred.

The mechanical and electrical imbalances listed earlier were simulated.

4.4.1 Mechanical Imbalance

A rotor imbalance was simulated by attaching a 0.3 kg mass block with distance to center of the shaft 80 mm to the load disc. For \( f_r = 9 \) Hz, Fig. 4.11 shows how spectral comparisons of mechanical imbalance were performed.

The reference spectrum was first established as baseline for the WT in good condition. When a new signal was recorded with an imbalance of 0.3 kg mass block added to the load disc, the frequency spectra was calculated and compared with the reference. By subtracting the two at identical frequency lines, a “difference” spectrum was obtained.

From the Fig. 4.11, 0.3 kg of increase in the imbalance force (inertia force) causes bearing 1X vibration from 0.1071 g to 0.1116 g, which is about 4%.

One of the difficulties with spectrum comparison is caused by small fluctuations in rotating speeds. The bottom part of Fig. 4.11 was distorted by the very small changes in shaft speed. These problems can be overcome with the use of constant percentage bandwidth, which is not the scope of this research [36].
Figure 4.11 Spectrum comparisons at 1X for mechanical imbalance
4.4.2 Electrical Imbalance

Electrical imbalance was simulated by decreasing one of the resistances in the load bank from 3.6 \( \Omega \). For \( f_r = 9 \) Hz, Fig. 4.12 shows how spectral comparisons of electrical imbalance were performed.

The reference spectrum was first established as baseline for the test rig in good condition. When a new signal was recorded with the electrical imbalance described above, the frequency spectra was calculated and compared with the reference. By subtracting balanced from the unbalanced spectral densities, a “difference” spectrum was obtained, shown in Fig. 4.12. The magnitude of the 1X peak increased from 0.1128 g to 0.1136 g when the resistance was reduced from 3.6 \( \Omega \) to 1.8 \( \Omega \), and there was about a 0.7% increase in the root mean square (RMS) vibration level. The magnitude increased to 0.1167 g when the resistance reduced to 0.9 \( \Omega \) and the RMS level increased about 3.5% the balanced case.

Figure 4.12 Spectrum comparisons for electrical imbalance (continued)
Figure 4.12 Spectrum comparisons for electrical imbalance
4.5 Wavelet Power Spectrum Analysis

Wavelet analysis is appropriate for characterizing machine vibration signatures with narrow frequency bands lasting for a short time period. Wavelets have the benefit of a local outlook, a multi-scaled outlook, co-operation between scales, and a time-scale analysis [62]. They demonstrate that Fourier analysis is not the only possible method of signal analysis and that basis made of other functions such as Daubachies wavelet, Morlet and Mery wavelet can be very useful for some transient signals.

The wavelet transform is a mathematical tool that decomposes a signal into a representation that shows signal details and trends as a function of time. This representation can be used to characterize transient events, reduce noise, compress data, and perform many other operations. The main advantage of wavelet methods over traditional Fourier methods is the use of localized basis functions. Localized basis functions are ideal for analyzing signals containing discontinuities and sharp spikes.

4.5.1 Wavelet Packet Transform (WPT)

The discrete wavelet transform is a multi-stage filtering process, also known as a multi-scale decomposition process, in which the discrete signal is convolved with a low pass filter and a high pass filter, resulting in two sets of coefficients: the approximation coefficients and the details coefficients [38]. The approximation coefficients represent the high-scale, low-frequency components of the signal, whereas the details coefficients represent the low-scale, high-frequency components.

In the WPT, not only is the approximation at a given level decomposed further, but also are the details. This gives a more flexible and wider base for the analysis of the monitored signals, and in a better time-frequency localization of faults, if any. The required discrete wavelet
analysis can then be implemented with a scaling filter, which is a low-pass filter related to the scaling function, and a wavelet filter, which is a high-pass filter related to the wavelet function [63]. Decomposition by WPT results in a wavelet packet tree. Figure 4.13 shows an example of a wavelet packet tree of three levels.

![Wavelet Packet Tree](image)

**Figure 4.13** An example of a wavelet packet decomposition tree of three levels

Each node of the WPT tree is indexed with a pair of integers \((j,k)\), where \(j\) is the corresponding level of decomposition and \(k\) is the order of the node position at that specific level. A vector of wavelet packet coefficients \(C_{j,k}\)'s corresponds to each node \((j,k)\), according to the basic step procedure.

**4.5.2 Wavelet Power Spectrum**

By properly decomposing signal into various frequency sub-bands, signal energy patterns in these frequency sub-bands can be used for machine condition monitoring and fault diagnosis.

Despite the lack of prior knowledge of the system frequency characteristics, the energy distribution changes when component condition changes. Band energy analysis based on the wavelet packet transforms is suitable for the evaluation of component conditions. The result of wavelet packet transform contains phase and amplitude information. For tracking energy
distribution, wavelet power spectrum is defined as $|C_n|^2$, where $C_n$ is the decomposition coefficient with $n$ point discrete representation [64].

It is not a trivial task to determine the right level of signal decomposition and therefore the frequency resolution. It is limited by the sampling frequency and also depends on the system frequency characteristics. In this work, the vibration sensor has an effective measurement frequency range 2 Hz to 4 kHz. System frequency characteristics are unknown. Also, too many levels of decomposition may cause serious frequency leakage. Through trial-and-observation, a 10-level WPT using Daubechies-18 wavelet basis was employed for signal decomposition. Band energy was then calculated at the 10-th level decomposition. Frequency band width is listed in Table 4.1.

Let $C_{j,k,i}$ denote the decomposed coefficient set at node $(j, k)$ which has $i$ elements. Each node coefficient measures a specific sub-band frequency content. The energy $E_{j,k}$, at wavelet packet node $(j, k)$ is defined in [65]:

$$E_{j,k} = \sum_l C_{j,k,l}^2$$

(4.10)

where $i = 1, 2, \ldots, 2^j$ and $n$ is the sample number of the digitized signal $x(n)$.

The energy distribution was normalized by dividing the band energy by the total energy of a particular level. In band $k$ at decomposition level $j$, the normalized energy is calculated as:

$$R_{j,k} = \frac{E_{j,k}}{\sum_k E_{j,k}}$$

(4.11)

where $k = 0, 1, \ldots, 2^j-1$. 
Table 4.1 Frequency band width by 10-level WPT decomposition

<table>
<thead>
<tr>
<th>Level</th>
<th>Frequency Band Width (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1024</td>
</tr>
<tr>
<td>1</td>
<td>512</td>
</tr>
<tr>
<td>2</td>
<td>256</td>
</tr>
<tr>
<td>3</td>
<td>128</td>
</tr>
<tr>
<td>4</td>
<td>64</td>
</tr>
<tr>
<td>5</td>
<td>32</td>
</tr>
<tr>
<td>6</td>
<td>16</td>
</tr>
<tr>
<td>7</td>
<td>8</td>
</tr>
<tr>
<td>8</td>
<td>4</td>
</tr>
<tr>
<td>9</td>
<td>2</td>
</tr>
<tr>
<td>10</td>
<td>1</td>
</tr>
</tbody>
</table>

4.5.3 Mechanical Imbalance

Figure 4.14 shows the results of normalized wavelet energy spectrum of the vibration signals with constant speed input 9 Hz collected from the accelerometer for rotor with same
0.3 kg mass block and without mass block used in the section 4.4.1. Results were calculated using 10-level WPT decomposition with Daubechies-18 basis function on the signals representing two different rotor conditions.

From the results, the normalized energy distribution is affected by the different conditions. For the vibration signal, the energy has a trend of shifting to a lower frequency range with increasing mechanical imbalance. The lower frequency matches with $f_r$. Energy at frequency sub-band 9 Hz increase with the mechanical imbalance.

4.5.4 Electrical Imbalance

![Normalized wavelet power spectrums on electrical imbalance](image)

**Figure 4.15** Normalized wavelet power spectrums for electrical imbalance

Figure 4.15 shows the results of normalized wavelet energy spectrum of the vibration signals with constant speed input 9 Hz collected from the accelerometer for one resistor with
3.6 Ω, 1.8 Ω and 0.9 Ω. Results are calculated using 10-level WPT decomposition with Daubechies-18 basis function on the signals representing three different rotor conditions.

Figure 4.15 shows that the normalized energy distribution is affected by different electrical imbalances. For the vibration signal, the energy has a trend of shifting to a lower frequency range with increasing electrical imbalance. The lower frequency matches with $f_r$. Energy at frequency sub-band 9 Hz increase with the electrical imbalance.

Wavelet power spectrum analysis has advantage on incipient faults detection. This work demonstrates the superiority of the proposed approach over the traditional FFT-based one. However, mechanical and electrical imbalances can’t be distinguished by this method.

4.6 Voltage Analysis

Voltage signals from the PMG were collected simultaneously with vibration signal. FFT of voltage was investigated for the mechanical and electrical imbalances.

4.6.1 Mechanical Imbalance

![Spectrum analysis on voltage signal using FFT on mechanical imbalance](image)

**Figure 4.16** Voltage analysis for mechanical imbalance
Mechanical imbalance was simulated by adding same 0.3 kg mass block to the load disc. The FFT of voltage measurement collected for $f_r = 9$ Hz was computed and shown the results in Fig. 4.16.

All the significant peak values shown in Fig. 4.16 are identical to the ones in Fig. 4.9. The voltage magnitude at 74.75 Hz, which is the power line frequency, changed from 3.991 V to 4.121 V which is about a 0.75% difference. The mechanical imbalance does not appear in the voltage analysis.

### 4.6.2 Electrical Imbalance

![Spectrum analysis on voltage signal using FFT on electrical imbalance with 1/2 resistor](image)

![Spectrum analysis on voltage signal using FFT on electrical imbalance with 1/4 resistor](image)

**Figure 4.17** Voltage analysis for electrical imbalance

75
Electrical imbalance was simulated by adjusting one phase resistance from $3.6 \, \Omega$ to $1.8 \, \Omega$ and $0.9 \, \Omega$. The resistance on the other two phases was kept at $3.6 \, \Omega$. The FFT of voltage measurement collected at PMG running at 9 Hz was computed and shown the results in Fig. 4.17.

The significant peak values shown in Fig. 4.17 are different to the ones in Fig. 4.9. The results can be compared with those in Table 4.2.

**Table 4.2 Voltage magnitude comparisons of electrical imbalances**

<table>
<thead>
<tr>
<th></th>
<th>Balanced</th>
<th>½ resistance</th>
<th>¼ resistance</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Magnitude</td>
<td>% difference</td>
<td>Magnitude</td>
</tr>
<tr>
<td>Magnitude ($f_r = 74.75$ Hz)</td>
<td>3.991</td>
<td>3.848</td>
<td>3.58%</td>
</tr>
<tr>
<td>Magnitude ($3f_r$)</td>
<td>0.5486</td>
<td>0.5588</td>
<td>1.86%</td>
</tr>
</tbody>
</table>

The voltage magnitude at $f_r$ decreased when the resistance reduced. The voltage magnitude at $3f_r$ increased shown from the results when the resistance reduced which means electrical imbalance increased. The further analysis is required to find out the reasons behind for changing of $f_r$ and $3f_r$ with electrical imbalance. The electrical imbalances were seen from the voltage analysis but the changes are small compared to the changes in the load resistance.

4.7 Chapter Summary

The preliminary analysis such as spectrum analysis, waterfall baseline, spectrum comparison analysis, wavelet spectrum analysis and voltage analysis were investigated under constant speed.
Chapter Five: Preliminary Vibration Analysis under Variable Speed

5.1 Background

Vibration transducers produce time series waveforms containing many specific signatures. It is important to understand these different vibration signatures and how to properly extract them under varying speed for further analysis.

There are a variety of different types of signal complexities, corresponding to different vibration phenomena as represented below:

- Some signals have long time duration but narrow bandwidth such as rub and buzz noise.
- Some signals have short time duration but wide bandwidth such as impact or transient.
- Some signals have short time duration but narrow bandwidth such as decayed resonance.
- Some signals have time-varying bandwidth such as an imbalance shaft generating vibration and noise dependent on machine speed.

Understanding the system being monitored and its vibration signals is always the first step in vibration applications. This was the topic of the previous chapter. Next step is to choose a proper algorithm to extract features of interest from the raw signal. Signals collected from the test rig under variable speed have a time-varying narrow bandwidth, and so are non-stationary. There are many algorithms such as order analysis and time-frequency analysis for time-varying vibration signals. These algorithms provide the ability to properly analyze and monitor PMGs.

Traditional frequency analysis techniques such as the FFT are not adequate for non-stationary signals because they are based on the assumption that the signal is stationary. Vibration analysis techniques directly based on FFT are unable to effectively deal with variable speed signals [3].
To begin the analysis of time varying frequency, a sinusoidal speed variation of $f_r$ with mean value of 9 Hz, magnitude 1 Hz and frequency 0.1 Hz was chosen. Three vibration analysis techniques: short time Fourier transforms (STFT), continuous wavelet transforms (CWT), and order analysis were performed and compared as described below. The same mechanical and electrical faults were used for the analysis.

5.2 Short Time Fourier Transform Analysis

STFT analysis uses a fixed sized window to limit the signal analysis to a short time period. In other words, it conducts FFT on a small portion of data at a time. Hence, multiple signal spectrums can be generated over time. STFT is evaluated by applying a windowing function to the original time signal and evaluating the Fourier transform on the resulting finite length time signal. The STFT of a time signal $X(t)$ over a window size $T$, is given by

$$S(t,f) = \int_{t-T/2}^{t+T/2} X(\tau)w(\tau-t)e^{-j2\pi f \tau}d\tau$$

(5.1)

where $w(\tau)$ is a window function which moves with the signal. The amplitude squared $|S(t,f)|^2$ is displayed on the time-frequency diagram [38]. This is known as the spectrogram. It shows how the energy of a signal is distributed in the time-frequency domain. The colour intensity shows the power of the signal at the corresponding time and frequency. The result can be displayed on a 3-D waterfall graph or a 2D map representation.

The following parameters of STFT were used for analysis:

- number of data points = 256, which is the FFT sample length
- Window: Hamming window of length 256
- The number of samples that each segment overlaps: 250
- Sampling rate: 256 Hz
Under the sinusoidal speed variation described above, the STFT power spectrogram is illustrated in Fig. 5.1.

![STFT Spectrogram of Sinusoidal Speed Input](image)

**Figure 5.1** STFT spectrogram under sinusoidal variation

The results are displayed as a spectrogram shown in jet colour map, which shows how the magnitude of the vibration signal is distributed in the time-frequency domain.

Because the STFT power spectrogram in Fig. 5.1 follows the sinusoidal variation in speed, a natural thought was to find out how the frequency was substituted by harmonics, or orders of the fundamental speed of the machine, where the first order corresponds to $f_r$ and the 3.6th order corresponds to $3.6f_r$. An interpolation algorithm was written to determine the shaft speeds at certain time based on the original speed measurement. The new time axis is different with original sampling time after STFT. Then frequency domain is mapped to order domain compared to the shaft speed of the machine at certain time. In the time domain, the above algorithm was carried out as normal FFT in the same small window. The small window was shifted to next data set and so on. The result from different windows were combined together to observe the condition of the machine.
Under the same sinusoidal speed variation described above, the modified STFT power spectrum is illustrated in Fig. 5.2.

![Modified STFT Spectrum](image)

**Figure 5.2** Modified STFT spectrum under sinusoidal variation

The results are displayed as a spectrum, which shows how the magnitude of the signal is distributed in the order domain. The various colours distinguish the different window data sets. It is shown that the significant first peak is around order 3.6 and the second significant peak is around order 1.

Figure 5.1 and Fig. 5.2 show that:

- The orders of the peak magnitudes of signal do not follow the speed curve as sinusoidal pattern. The effect of varying speed was successfully removed;
- The dominant vibration amplitude at approximately $3.6f_r$, matches the characteristic frequency of the bearing outer raceway defect;
- The second dominant vibration amplitude occurs at a frequency corresponding to $f_r$;
A shortcoming of the STFT analysis is that the dominant frequencies change with shaft speed. It can only show that the curve of the peak frequencies looks similar to sine wave speed input, which can only be used indirectly to detect the fault.

Another shortcoming of the STFT approach is that the window size is fixed. A high resolution in spectrum requires a large window which results in poor localization in time due to the uncertainty principle [37]. Conversely, a small window offers sharp time localization however compromises spectrum resolution. There is a trade-off in the choice of window size.

5.3 Continuous Wavelet Transform Analysis

In contrast to the STFT analysis, wavelet analysis uses variable window size. It allows the use of long time intervals when low-frequency information is wanted, and shorter windows when high-frequency information is wanted.

Wavelet analysis makes use of various predefined mother wavelets. Wavelets have a good concentration and resolution trade-off between the time and frequency domain because wavelets have limited bandwidth in the frequency domain and compact support in the time domain. A pattern matching algorithm then compares the signal to the known library of wavelets representing identified faults in the particular components. The pattern matching algorithm will then return a coefficient indicating the “goodness” of the match. A high coefficient indicates a good wavelet match and thus can be used to indicate a defect.

The following parameters of CWT were used for analysis:

- Wavelet: db3, which is the Daubechies wavelet of order 3.
- Scale: 1 to 64 with step 1;
- Signal sampling rate: 256 Hz
• Coloration mode: init+all scales+abs (Three parameters are used to color the coefficients.)

Init or current — When init is selected, coloration is performed with all the coefficient values. When current is selected, only the coefficients displayed in the current axis limits are used.

By scales or all scales — When by scale is selected, the coloration is done separately for each scale. When all scales is selected, all scales are used.

Abs — When abs is selected, the absolute values of the coefficients are used.

Figure 5.3 CWT scalogram under sinusoidal speed variation

The analyzed signal is illustrated on the top section of Fig. 5.3. Scales are shown on the y-axis of the bottom half figure. Like the concept of frequency, scale is another useful property of signals. To go beyond colloquial descriptions such as "stretching" or "shrinking", the scale factor was introduced. The smaller the scale factor, the more "compressed" the wavelet which
represents rapid changing details with high frequency. Conversely, the larger the scale factor, the more stretched the wavelet which represents slow changing and coarse features with low frequency. This general inverse relationship between scale and frequency holds for signals in general. While there is a general relationship between scale and frequency, no precise relationship exists.

Figure 5.3 shows that:

- The peak magnitude of signal follows the speed curve in sinusoidal pattern;
- The dominant vibration amplitude at approximately $3.6f_r$ shown in Fig. 5.3 matches the characteristic frequency of the bearing outer raceway defect.
- The second dominant vibration amplitude at a frequency corresponding to $f_r$ shown in Fig. 5.4 matches the frequency of rotation.

The shortcoming of the CWT analysis is that the dominant frequencies change with shaft speed and can only be used indirectly to detect the fault, similar to STFT analysis.

5.4 Order Analysis

Many features in machine vibration signals are directly related to the running speed of a machine such as imbalance, misalignment, gear mesh, and bearing defects. Even if the FFT is able to clearly analyze the data and show the power spectrum for the machine, it is not capable of easily tracking speed-varying harmonics.

Order analysis is specifically geared to the frequency changes as the rotational speed of the machine changes [47]. It samples in time and then “resample” from the time domain into the angular domain through interpolation, aligning the signal with the angular position of the PMG shaft. This negates the effect of changing frequencies on the FFT algorithm, which normally is not convenient to handle such phenomena. Data at constant angle increments in angle-domain
are obtained. Therefore, signals in time domain are changed into pseudo-stationary ones in angle-domain. Resampling combines the speed measurements taken from the VFD on the drive with the vibration measurements and interpolates the vibration measurements into a data point per fraction of angular rotation. The slip did not vary significantly and less than 2% under different speed. The speed correction was considered into order analysis. There is no significant impact for result of the order analysis.

Once in the angular domain, an STFT can be performed on the angular domain vibration measurement to produce what is known as an order spectrum.

Under sinusoidal speed variation mentioned above, the order analysis spectrum shown in jet colour map is shown in Fig. 5.4.

![Figure 5.4 Order Spectrogram under sinusoidal speed variation](image)

Notice that the $3.6f_r$ peak is no longer in terms of frequency but harmonics, or orders of the fundamental speed of the machine, where the first order corresponds to $f_r$ and the $3.6^{th}$ order corresponds to $3.6f_r$. The $3.6^{th}$ harmonic is no longer shifted as $f_r$ changes, making it much easier to monitor the harmonics of a rotating system. The dominant vibration amplitude at
approximately $3.6f_r$ shown in Fig. 5.4 matches the characteristic frequency of the bearing outer raceway defect. Furthermore, the fundamental generator frequency is not shifted.

Various speed patterns were simulated including some transients in a series of additional tests with different peak and duration. One of such speed inputs is 180~520 rpm illustrated in Fig. 5.5. The sampling rate is 2048 Hz. The abscissa is sampling point index and the coordinate is speed in rpm.

![Figure 5.5 Time-varying speed curve](image)

With the above speed input profile, the order analysis spectrum of the vibration signals in jet color map is in Fig. 5.6.

![Figure 5.6 Order spectrogram for the speed variation shown in Fig.5.5](image)
The order analysis results show that the 3.6\textsuperscript{th} harmonic and 1\textsuperscript{st} harmonic are always clearly detected and do not shift with speed variation for various speed patterns. The magnitude of the signals can be used as a baseline for condition monitoring for similar speed variations. This demonstrates that order analysis is a simple, intuitive and reliable technique for vibration analysis under variable speed.

The above order analysis is not suitable for signals with impulses and rapid transients. Also one of the limitations is the dynamics of the bearing. For example, any significant time dependent dynamics will be lost in order analysis.

Three time-frequency analysis such as STFT, CWT and order analysis were investigated in the research. The bearing fault characteristic frequency 3.6X and fundamental frequency 1X were clearly shown on these three time-frequency analysis techniques. Order analysis is a simple, intuitive and reliable method for wind turbine under variable speed due to the speed variation from wind.

The magnitude of the signal levels is important as they need to be tracked with time over variations in shaft speed, which can be used as baseline with certain shaft speed for future research. The resolution can be improved to see the difference more clearly; however the magnitude variation is less than 5% in the speed range from 110 rpm to 600 rpm as per Fig. 4.10. The magnitude would increase significantly if the bearing deteriorates in the future.
Chapter Six: Conclusions and Future Work

6.1 Conclusions

The test rig was designed and built to allow research in the condition monitoring and fault diagnosis of small wind turbine generators. The important features include variable speed operation of the 500 W permanent magnet generator driven by a 1.5 kW three phase AC induction motor by the use of a variable frequency drive (VFD). Mechanical and electrical imbalances were simulated. To show the quality of the signals from an accelerometer mounted near the rear generator bearing, preliminary analysis techniques were investigated in the thesis. Spectrum analysis, waterfall baseline, spectrum comparison analysis and wavelet power analysis and voltage analysis were used for the case of constant shaft speed. Short time Fourier transforms, continuous wavelet transforms and order analysis were used for variable speed. It has been concluded from these investigations that:

- The test rig was designed and built successfully to simulate a small PMG under variable running speed. It is capable of allowing the collection and analysis of stationary and non-stationary vibration signals and useable for future research and development.
- A suitable accelerometer was selected and successfully used for vibration signal collection. The best sensor location is at 6 o’clock on the outside rim of bearing housing.
- The characteristic frequency of the ball bearing outer race fault was shown at 3.6X in spectrum analysis and waterfall baseline.
- Mechanical imbalance was shown at 1X by spectrum comparison and wavelet spectrum analysis.
- Electric imbalance was shown in spectrum comparison analysis, wavelet packet analysis.
• Voltage analysis is not sufficient for machinery fault detection such as bearing fault, and mechanical imbalance. However, it is effective for electrical imbalance.

• STFT, CWT and order analysis are suitable for vibration analysis under variable speed. It is evident that preliminary analysis using order analysis offers a simple, intuitive and reliable technique to perform well on the test rig under variable speed.

6.2 Future Work

It is evident from this work that order analysis offers a promising way for condition monitoring and fault detection in PMG. Future work will be required to develop these techniques, including:

• Load and control system imbalance

• The suitability of on-board microprocessor performance of condition monitoring

• Pattern classification such as artificial neuron networks, Bayesian classifier and support vector machine

• Electrical fault study
References


APPENDIX A: GL-PMG-500A SPECIFICATION SHEET

Wind Turbine Permanent Magnet Generator/Alternator
Ginlong Technologies GL-PMG-500A
World Leading Professional Wind Turbine Parts Supplier

### Electrical Specification

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<tr>
<th>Specification</th>
<th>Value</th>
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<tbody>
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<td>Rated Output Voltage</td>
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</tr>
<tr>
<td>Rated Rotation Speed (RPM)</td>
<td>480</td>
</tr>
<tr>
<td>Rated AC Current at Rated Output (A)</td>
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<tr>
<td>Rated Output Power (kW)</td>
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<td>Power Frequency (Hz)</td>
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<td>Output Voltage Ripple %</td>
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<td>Insulation Class</td>
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<tr>
<td>Generation Configuration</td>
<td>3-Phase 3-wire/6-wire AC output</td>
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<tr>
<td>Design Lifeline</td>
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### Mechanical Specification

<table>
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<td>Weight (kg)</td>
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</tr>
<tr>
<td>Starting Torque (Nmm)</td>
<td>≥ 175</td>
</tr>
<tr>
<td>Resistance (Ω)</td>
<td>≤ 0.004</td>
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<tr>
<td>Bearing Type</td>
<td>High standard 6000/6200/6300 (Cm) SKF/NSK (Bear)</td>
</tr>
</tbody>
</table>

### Material Specification

<table>
<thead>
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<th>Material</th>
<th>Specification</th>
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<td>Shaft Material</td>
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<tr>
<td>Shaft Rating</td>
<td>High standard SKF or NSK bearing</td>
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<tr>
<td>Outer Frame Material</td>
<td>High standard Alumina with 175°C heat resistance</td>
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<td>Core Material</td>
<td>Silicon Steel (1.02% Silicon, 0.005% Phosphorus)</td>
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<tr>
<td>Insulation Material</td>
<td>YbFe11 (Yttrium Ferrite)</td>
</tr>
<tr>
<td>Winding Temperature Rating</td>
<td>190° degrees Celsius</td>
</tr>
<tr>
<td>Insulation Material</td>
<td>High specification nickel steel</td>
</tr>
</tbody>
</table>

---

![GL-PMG-500A PMG Power Curve](image1)

![GL-PMG-500A PMG Open Circuit Voltage](image2)

![GL-PMG-500A PMG Input Torque Curve](image3)

---

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APPENDIX B: DATA SHEET FOR PDH 00208TE2

TECHNICAL DATA SHEET

MOTOR TYPE: AEHE

<table>
<thead>
<tr>
<th>CATALOG No.</th>
<th>PDH00208TE2</th>
<th>ISSUED: 31/05/2011</th>
</tr>
</thead>
</table>

NAME PLATE INFORMATION

<table>
<thead>
<tr>
<th>HP</th>
<th>Pole</th>
<th>RPM</th>
<th>Frame</th>
<th>Voltage</th>
<th>Hz</th>
<th>Phase</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>8</td>
<td>860</td>
<td>21ST</td>
<td>230</td>
<td>60</td>
<td>3</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Enclosure</th>
<th>Ins. Class</th>
<th>Service Factor</th>
<th>Time Rating</th>
<th>NEMA Design</th>
<th>Rated Amb.</th>
<th>Rated Altitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>TEFC</td>
<td>F</td>
<td>1.15</td>
<td>Continuous</td>
<td>B</td>
<td>-20 to 40°C</td>
<td>&lt;3300 ft</td>
</tr>
</tbody>
</table>

TYPICAL PERFORMANCE

<table>
<thead>
<tr>
<th>Efficiency (%)</th>
<th>Power Factor (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Full Load</td>
<td>3/4 Load</td>
</tr>
<tr>
<td>Nom</td>
<td>1/2 Load</td>
</tr>
<tr>
<td>82.5</td>
<td>82.5</td>
</tr>
<tr>
<td>84.0</td>
<td>82.5</td>
</tr>
<tr>
<td>84.0</td>
<td>82.5</td>
</tr>
<tr>
<td>50.0</td>
<td>42.5</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Torque (lb-ft)</th>
<th>Current (A)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Full Load</td>
<td>Locked Rotor</td>
</tr>
<tr>
<td>12.1</td>
<td>%FLT</td>
</tr>
<tr>
<td>190</td>
<td>%FLT</td>
</tr>
<tr>
<td>170</td>
<td>275</td>
</tr>
<tr>
<td>4.72</td>
<td>68</td>
</tr>
<tr>
<td>50</td>
<td></td>
</tr>
</tbody>
</table>

NEMA KVA

<table>
<thead>
<tr>
<th>Code</th>
<th>Inertia</th>
<th>WR²</th>
<th>Max. Allowable</th>
<th>Safe Stall Time (s)</th>
<th>Noise Level</th>
</tr>
</thead>
<tbody>
<tr>
<td>L</td>
<td>0.386</td>
<td>59</td>
<td>385</td>
<td>80</td>
<td>56</td>
</tr>
</tbody>
</table>

VFD DUTY INFORMATION

<table>
<thead>
<tr>
<th>Speed Range</th>
<th>VFD</th>
<th>S.F.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant Torque</td>
<td>Variable Torque</td>
<td>Constant Power</td>
</tr>
<tr>
<td>10 : 1</td>
<td>20 : 1</td>
<td>60-120Hz</td>
</tr>
</tbody>
</table>

ADDITIONAL INFORMATION

<table>
<thead>
<tr>
<th>Bearings</th>
<th>Approx Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>DE</td>
<td>NDE</td>
</tr>
<tr>
<td>6302ZZ</td>
<td>6306ZZ</td>
</tr>
<tr>
<td>167</td>
<td></td>
</tr>
</tbody>
</table>

Issued By: Yang, Kang

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APPENDIX C: SOLIDWORKS DRAWINGS FOR TEST RIG

<table>
<thead>
<tr>
<th>ITEM NO.</th>
<th>PART NUMBER</th>
<th>DESCRIPTION</th>
<th>QTY.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Pad</td>
<td>Vibration isolation 4&quot;x4&quot;x1/2&quot;</td>
<td>4</td>
</tr>
<tr>
<td>2</td>
<td>Concrete Base</td>
<td>1200mm x 800mm x 300mm concrete</td>
<td>1</td>
</tr>
<tr>
<td>3</td>
<td>Flg Base</td>
<td>Flat bar 3&quot; x 1/2&quot;</td>
<td>2</td>
</tr>
<tr>
<td>4</td>
<td>Skld</td>
<td>Channel steel 4&quot;x1/2&quot;</td>
<td>1</td>
</tr>
<tr>
<td>5</td>
<td>Shim</td>
<td>H32 1.5&quot; x 1.25 x 1.25 x 18&quot;</td>
<td>2</td>
</tr>
<tr>
<td>6</td>
<td>WPV</td>
<td>1/2&quot; Plate 200mm x 200mm</td>
<td>1</td>
</tr>
<tr>
<td>7</td>
<td>KPH</td>
<td>1/2&quot; Plate 1.5&quot; x 2&quot;</td>
<td>1</td>
</tr>
<tr>
<td>8</td>
<td>Motor_Support</td>
<td>Flat bar 3&quot; x 1/2&quot; x 17&quot;</td>
<td>2</td>
</tr>
<tr>
<td>9</td>
<td>PMG_Support</td>
<td>Flat bar 3&quot; x 1/2&quot; x 17&quot;</td>
<td>2</td>
</tr>
</tbody>
</table>

Assembly_TestRig

Appendix C1
Plate thickness: 1/2"
plate thickness: 1/2"
APPENDIX D: ACCELEROMETER M50 SPECIFICATION SHEET

ISOTRON® Accelerometer

Model 50/50M1
- Low-Cost Vibration Sensor
- Lightweight (3.8 gm)
- Milli-g’s Resolution
- Easily Mounted
- Ideal for R&D Lab Tests or Full-Scale Modal Testing

DESCRIPTION
The ENDEVCO® Model 50 and 50M1 are small piezoelectric accelerometers with integral amplifiers, developed specifically for modal measurements or OEM vibration applications. In addition to having minimum unit-to-unit phase deviations, the built-in measurement has been configured to work in a constant current mode with a supply voltage as low as ±12Vdc, as well as a car battery. The units are designed to be mounted with our adhesive or integral high-strength magnet (50M1). A dielectric layer on the base isolates the case ground from the mounting surface to eliminate the potential ground loops. These accelerometers are hermetically sealed to provide long-term reliability even in harsh environments, and their light weight (3.8 gm) effectively minimizes mass loading effects. The inside of the protective vinyl cap can be filled with RTV to further improve resistance to moisture at the connection junctions.

For your convenience, the Model 50 and 50M1 come with a 3-meter pair of output wires attached, ready to be used right out of the box. A matching low-cost, 10-channel power supply (Model 4475) is also available. Other ENDEVCO ISOTRON signal conditioners, such as Model 123, 2792B, 2793 or 4414E, can also be used with this unit.
**ENDEVCO MODEL 50/50M1**

**ISOTRON® Accelerometer**

**SPECIFICATIONS**

The following performance specifications contain IEEE-417-2 (1980) and are typical values, referenced at 77°F (25°C), 4 mA, and 100 Hz unless otherwise noted. Calibration data transferable to National Institute of Standards and Technology (NIST) is supplied.

<table>
<thead>
<tr>
<th>Dynamic Characteristics</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Range</strong></td>
<td>g</td>
</tr>
<tr>
<td><strong>Voltage Sensitivity</strong></td>
<td>mV/g</td>
</tr>
<tr>
<td>±5% Typical</td>
<td></td>
</tr>
<tr>
<td><strong>Frequency Response</strong></td>
<td>Hz</td>
</tr>
<tr>
<td>± 0.0%</td>
<td></td>
</tr>
<tr>
<td><strong>Amplifier Response</strong></td>
<td>Hz</td>
</tr>
<tr>
<td>± 0.0%</td>
<td></td>
</tr>
<tr>
<td><strong>Temperature Response</strong></td>
<td>°C</td>
</tr>
<tr>
<td>± 0.0%</td>
<td></td>
</tr>
<tr>
<td><strong>Amplifier Linearity</strong></td>
<td>%</td>
</tr>
<tr>
<td>± 0.0%</td>
<td></td>
</tr>
</tbody>
</table>

**Output Characteristics**

<table>
<thead>
<tr>
<th>Output</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Voltage</td>
<td>Acceleration directed into the base of the unit produces positive output</td>
</tr>
</tbody>
</table>

| DC Output Bias Voltage | ± 0.5 mV typical |
| DC Output Reference | ± 150 mV |
| Full Scale Output Voltage | ± 200 mV |
| Resolution to 1 Hz | ± 0.001 in |
| Grounding | Signal ground isolated from mounting surface |

**Power Requirement**

<table>
<thead>
<tr>
<th>Supply Current</th>
<th>mA</th>
</tr>
</thead>
<tbody>
<tr>
<td>± 20 to ± 100</td>
<td></td>
</tr>
</tbody>
</table>

**Warm-up Time**

<table>
<thead>
<tr>
<th>Time</th>
<th>min</th>
</tr>
</thead>
<tbody>
<tr>
<td>± 2</td>
<td></td>
</tr>
</tbody>
</table>

**Environmental Characteristics**

<table>
<thead>
<tr>
<th>Temperature Range</th>
<th>°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>± 45 to ± 125 (20°C to 55°C)</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Humidity</th>
<th>%RH</th>
</tr>
</thead>
<tbody>
<tr>
<td>Non-condensing Sealed</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Shock Limit [G]</th>
<th>G</th>
</tr>
</thead>
<tbody>
<tr>
<td>± 2000</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Base Strain Sensitivity</th>
<th>mV/g</th>
</tr>
</thead>
<tbody>
<tr>
<td>± 0.001</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Electrodynamic Sensitivity</th>
<th>mV/g</th>
</tr>
</thead>
<tbody>
<tr>
<td>± 0.003</td>
<td></td>
</tr>
</tbody>
</table>

**Physical Characteristics**

<table>
<thead>
<tr>
<th>Dimensions</th>
<th>See Outline Drawing</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Weight (wire)</th>
<th>g (oz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>26.4 (1.4)</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Case Material</th>
<th>Stainless Steel</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Mounting</th>
<th>Adhesive or Integral Magnet (50M1)</th>
</tr>
</thead>
</table>

**Calibration**

<table>
<thead>
<tr>
<th>Sensitivity</th>
<th>mV/g (1G)</th>
</tr>
</thead>
<tbody>
<tr>
<td>± 0.001</td>
<td></td>
</tr>
</tbody>
</table>

**Accessories**

- 26 AWG OUTPUT WIRES (3 METERS) SOLDERED TO TERMINALS
- OPTIONAL ACCESSORIES:
  - Models 2925/00A, 2925/10A, 2925/15A, 2925/20A TERMINAL MOUNTING BLOCK
  - 3024-10 CABLE ASSEMBLY
  - PN 25040 ADHESIVE MOUNTING KIT
  - PN 4478 10 CHANNEL ISOTRON SIGNAL CONDITIONER

**Notes:**

1. Compliance voltages as low as 10V may be used in combination with a constant current source to provide power to the accelerometer. However, the dynamic range may be limited to a maximum of 500 g.
2. Built-in mechanical stop inside the assembly also greatly increases the shock survivability of the accelerometer.
3. Depending on the demands and end-use environmental requirements, adhesive such as silicones, polycylics, and silicone release polymer glue may be used to mount the accelerometer temporarily to the test structure. An adhesive mounting kit (PN 01600) is available as an option from Endevco.

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**Maintain high levels of precision and accuracy using Endevco's battery-powered services. Call Endevco's rental center at 800-232-6750 for competitive rates, pricing, and turn-around time for these services as well as for options on our standard products.**

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**Endevco Corporation**

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