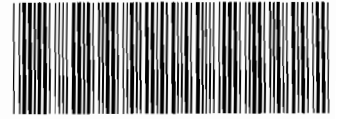


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UNIVERSITY OF CAPE TOWN

**THE POWER QUALITY OF WIND TURBINES IN SOUTH  
AFRICA AND THEIR IMPACTS ON DISTRIBUTION  
NETWORKS**

By

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## SYNOPSIS

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This thesis describes an investigation into the power quality of wind turbines and the impacts this could have on distribution networks. The main focus is on voltage fluctuations and flicker as grid connected wind turbines could have a huge impact on these, especially when connected to weak distribution networks

The interest in wind turbines has increased significantly over the past years in many countries worldwide. Three wind turbines have been installed in the Western Cape wind farm, Klipheuwel, South Africa. These were installed so that studies can be carried on to test the feasibility of wind generation in South Africa.

Many South African distribution networks are electrically weak networks that have relatively high impedance lines. Such networks suffer voltage-related problems. Distribution networks are designed to accept bulk electricity power from transmission lines and distribute it to customers. However, the connection of wind turbines and distribution networks in general could reverse the usual power flow.

The hypothesis, which states that “Despite the use of power electronics converters and modern machine designs, wind energy generators cause fluctuating voltage and flicker on weak feeders”, was formed. To prove or disprove this hypothesis, the following tasks were then drawn.

- a) To review existing information on power quality of wind turbines and the impacts they could have on distribution networks.
- b) To study different types of wind turbines and their behaviour.
- c) To conduct and analyse power quality studies of wind turbines in Klipheuwel
- d) To draw conclusions based on studies conducted

The review of work done by others identified voltage fluctuations and voltage flicker as the main power quality characteristics that wind turbines could affect. Wind turbines could either be a fixed speed turbine or a variable speed wind turbine. These wind turbines could either be fixed with an induction generator or a synchronous generator. Fixed speed wind turbines are identified as wind turbines with higher flicker emission than variable speed wind turbines. However, both types of wind turbines have been recognised as sources of voltage fluctuations because of wind speed fluctuations, which result to power fluctuations.

The findings of flicker emission studies conducted showed that flicker occurs during both switching and continuous operations. Flicker caused by switching operations is due to the turbine generator connection and capacitor switching. During turbine generator connection, high currents are drawn, which could result to voltage dips. Capacitor switching is followed by high frequency inrush currents, which could result to transient. For flicker during switching operations calculations, a wind turbine is characterised by a flicker step factor, which is a normalised measure of flicker emission due to a single worst case switching operation.

Flicker during continuous operations has been concluded to be as a result of power fluctuations emanating from the wind turbines. Power fluctuations are the results of wind speed fluctuations and tower shadow effects. The tower shadow effects affected the power output of the turbine. This is because every time the blade passes the tower, the power would drop. This power drop occurs 3 times per revolution for a three-bladed turbine. The method for assessing flicker emission during continuous operations assumes that a wind turbine is characterised by a flicker coefficient value, which is a normalised measure of flicker emission during continuous operations. Literature survey reveals that the type of wind turbines used determines whether flicker emission would be higher. For instance, flicker emission has been reported to be higher from variable speed wind turbines compared to fixed speed wind turbines.

The studies on voltage fluctuations and flicker were separated into two sections, one section from calculation and simulation on DigSilent, using an induction generator as a distributed generator example. This was chosen as most wind turbines use this

type of a generator. The voltage fluctuations were obtained by varying power output from the generator. From this exercise, it was shown that an induction generator with fluctuation power output result to voltage fluctuations at the terminals of the generator. The effects of X/R ratio of the grid on voltage variations were also studied. These were done to study the effects of the weakness of a distribution network. The studies showed that at low X/R ratios, i.e. an X/R ratio  $\leq 1$ , the voltage fluctuations are higher than at higher X/R ratios.

The second section is on actual measurements from the wind farm. These measurements were taken on Vestas V47 wind turbine, which uses an induction generator, with rated power output of 660kW. Measured data included active, reactive and apparent power output, voltage and currents, as well as flicker emission. The results obtained showed high flicker emission by a variable speed wind turbine. However, studies of a fixed speed wind turbine were not conducted to compare the impacts. The measured flicker increases with an increase in power output of the turbine.

The measured voltage on the studied wind turbine showed voltage fluctuation, which followed fluctuation seen on both wind speed and power output. These voltage fluctuations could be a threat to weak distribution network. However, the measured voltage fluctuations are still within the distribution network voltage limit.

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# 1. INTRODUCTION

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This report describes an investigation of the effects of wind generation on power quality of distribution networks. The main focus is on voltage fluctuations and flicker as grid connected wind turbines can have a significant effect when connected to weak distribution networks. Three wind turbines have been installed in the Western Cape wind farm, Klipheuwel, South Africa so that studies can be carried on to test the feasibility of wind generation in South Africa. Practical measurements were taken from one of the wind turbines for comparison with the theoretical studies.

## **1.1 Background and Objectives**

Distributed generation is the form of generating electrical energy into distribution networks. Distributed generation is used world wide including South Africa. Distributed generation can be applied as Combined Heat & Power (CHP), standby power, peak shaving, isolated generation, grid support, etc. There are several distributed generation technologies, including wind energy, photovoltaics, fuel cells and micro generators.

Many European countries have been using wind energy to generate electricity since the 19<sup>th</sup> century [23]. The first country to use wind turbines to generate electricity is Denmark [23]. Several units with capacity of 5 to 25 kW were in operation by 1910 [23]. Wind energy has been used widely throughout the world to pump water, to move ships, grind grains.

Southern Africa has been said to have good wind conditions along the southern African coastline and Indian Ocean islands [31]. However, there are some common obstacles to wind energy development in Southern Africa such as low electricity pricing, lack of government support, lack of incentives, lack of local manufacturers

(about 80% of all wind turbines sold world-wide are manufactured by European countries) [31]. Nevertheless, South Africa's first wind farm is in operation. Three wind turbines were installed at Klipheuwel between August 2002 and February 2003. The wind farm is the biggest in sub Saharan Africa.

The use of renewable energy resources has increased dramatically over years. However, the use of wind turbines introduces additional variability in power and can possibly affect the power quality of the grid where it is connected.

Studies have been conducted at the South African wind farm to investigate the power quality of the wind turbines and the impacts they could have on South African distribution systems.

## **1.2 Problem Statement**

Distribution networks are designed to operate with no generation on the distribution system. Distribution systems were designed to accept bulk power from the transmission system and distribute it to the customers. The power flows from the higher voltage level to the lower voltage level. But, with distributed generators penetrating, the power flows may be reversed and distribution system becomes an active source and no longer passive circuit [17]. This could have a negative effect on power quality of that particular distribution system. Wind turbines, in particular, have been said to be good examples of generators that cause voltage fluctuations and voltage flicker on distribution systems [17]. This could be because wind power has less predictable and controllable power production due to the variation in wind speed, tower shadow and turbulence. This variability of wind power output makes it more difficult for operators to maintain the quality of supply to consumers while operating the system economically. Inability to control power output is a problem especially on wind turbines that are connected to a weak distribution system.

The other problem is when wind turbines are connected to weak networks. Weak distribution networks have low X/R (impedance) ratios and relatively small transformer capacities. Since wind turbines produce fluctuating voltage, the

connection to distribution networks results in high voltage fluctuations on the network.

Given the challenges stated, a hypothesis that will guide the research was formed. The hypothesis is stated as follow:

“Despite the use of power electronics converters and modern machine designs, wind energy generators cause fluctuating voltage and flicker on weak feeders”.

The tasks needed to test the hypothesis are:

- e) To review existing information on power quality of wind turbines and the impacts they could have on distribution networks.
- f) To study different types of wind turbines and their behaviour.
- g) To conduct and analyse power quality studies of wind turbines in Klipheuwel
- h) To draw conclusions based on studies conducted

## **1.4 Approach and Method**

The experiments concerned in this investigation will be done on wind turbines in Klipheuwel, Cape Town, South Africa. Wind and power quality data used in this research will be taken only from the three new wind turbines in South Africa, which cannot represent all new wind energy generators. This is because distribution system constraints may differ from one country to another; hence, the effects of wind generation could be different from the ones in other countries.

The first part of the research will be carried out through a review of published literature on wind energy, which will be based mainly on work done in countries like Sweden, Norway, Ireland, Germany and many more, especially from Europe, as most work has been published from these countries.

The second part of the research includes an investigation and studies on power quality issues. This investigation includes the possible effects that wind turbines could have on power quality of distribution networks.

Practical measurements are taken at Klipheuwel to test the validity of the hypothesis.

Conclusions are then drawn based on the findings of the research.

## **1.5 Thesis Outline**

This report consists of seven chapters, outlined as follows:

Chapter 1 - In this chapter, the background of the investigation is discussed. The objectives of the research, the hypothesis of the research, which has led to literature survey on wind energy generators and their impact on distribution networks, are presented in this chapter.

Chapter 2 - Work done on distributed generation generators is presented in this chapter. Distributed generation and its technologies are defined as well as power quality issues. Power quality characteristics such as flicker and voltage variations are defined and explained.

Chapter 3 - This chapter gives a background on the South African wind farm. The possible impacts that each of the three wind turbines could have on distribution networks are presented in this chapter. Hence the studies on South African distribution networks are discussed. This chapter leads to a proper investigation on power quality issues and the relationship with wind energy generators.

Chapter 4 - Power quality issues are discussed both in general and specific to wind energy. Power quality characteristics are explained. These characteristics include voltage fluctuations, flicker, harmonics, etc. The investigation into power quality of wind turbines has resulted in two power quality characteristics being investigated.

This is due to the nature of distribution networks in South Africa, explained in chapter 3.

Chapter 5 - Presents voltage fluctuations and flicker emissions from wind turbines. Theoretical results are presented in this chapter.

Chapter 6 – Results obtained from practical measurements obtained from Klipheuwel wind farm are shown and discussed in this chapter.

Chapter 7 - Presents the conclusions based on the findings of the research.

University of Cape Town

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## 2. LITERATURE REVIEW

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Power quality studies of wind turbines are an area that has been covered extensively by many authors internationally. These studies have been of interest when these wind turbines are connected to distribution networks. This chapter identifies some of the power quality problems introduced by wind turbines to distribution networks according to the existing information.

Wind turbines are one of distributed generators found. Before wind turbines are introduced, it would be important to first understand the meaning of distributed generators. This would then lead to an understanding of wind turbines' definition and their connection to distribution network.

This chapter is divided into five sections. The first section deals with distributed generation definition and how different authors came to a Southern African definition. The second section presents wind energy and focussing on power produced from wind, the relationship between power and wind is also discussed. Different types of wind turbines are presented and explained. The third section deals with the connection of wind turbines to distribution networks. The fourth section describes power quality of wind turbines and the effects on distribution network. The last section is a summary of the key findings of the chapter.

### ***2.1 Distributed Generation***

Distributed generation has far many definitions, varying from country to country. For instance [17], refers to distributed generation as embedded generation, meaning generation which is connected to distribution network. On the other hand, CIGRE [17] defines distributed generation as generation that is; (i) not centrally planned, (ii) not centrally dispatched, (iii) usually connected to the distribution network, and (iv) smaller than 50-100MW. There are far many other definitions of distributed

generation from different authors in different countries. Other authors refer to distributed generation as dispersed generation.

The South African definition for distributed generation was derived under the following headings [9]:

- Interconnection voltage level
- Mode of operation
- Location
- Capacity
- Technology
- Ownership and planning
- Power delivery area

The South African definition was then defined as follows: [9].

“Distributed generation is any source of electric power that is interconnected with an electricity supply network at a system voltage level not exceeding 132kV. The generator is not centrally dispatched. It is not a trading participant in a power pool but usually responds to a tariff signal.”

Wind generation is then one of the technologies of distributed generation as it fits the definition of DGs in Southern Africa and worldwide. The following section deals with wind energy and literature concerning its' power quality performance as experienced by different authors in various countries.

## ***2.2 Wind Turbine Design***

Before discussing power quality of grid connected wind turbines, it is important to discuss the design of wind turbines, and how electricity is generated from wind energy.

Wind turbines convert mechanical energy into electric energy. Wind turbines include the rotor, generator, turbine blades and drive devices. The most common wind turbine is of a horizontal axis propeller type with three blades mounted on top of a tower. As the wind blows through the blades, the air exerts aerodynamic forces that cause the blades to turn the rotor.

The output power of a wind turbine is variable depending on the instantaneous wind speed.

Power from wind is given by the following equation [17]:

$$P = \frac{1}{2} C_p \rho V^3 A \dots\dots\dots(2.1)$$

Where

P = power in Watts

C<sub>p</sub> = power coefficient, which is a measure of how much of the energy in the wind is extracted by the turbine rotor.

ρ = air density

V = wind velocity (m/s)

A = swept area of rotor disc (m<sup>2</sup>)

Equation 2.1 shows that the output power increases with the cube of the wind speed until the rated power output is reached. The power from the wind turbine is limited to a rated power output at wind speeds of about 12 m/s and above. The following methods are used for limiting power output at rated power [24].

- (i) The turbine blades could be pitched away from the wind mechanically. This method is called pitch regulation.
- (ii) The power output could be limited by an aerodynamic limitation of the power. This method is known as stall regulation.

However, these methods do not stop the wind turbine's power output from fluctuating at wind speeds below 12m/s. The power output will vary due to variation in wind speed, turbulence and tower shadow.

At wind speeds greater than 25 m/s most wind turbines with aerodynamic design shut down [23]. This shut down is done automatically to protect the turbine from

any damages that may be due to high wind speed. The diagram below shows a design wind speed power curve of a 660kW-wind turbine, which shows the regulated power from the wind turbine. The output power between 12m/s and 25m/s is kept constant by aerodynamic designs. This means that wind speed change has no impact on power output in this region. However, in the region between 4m/s and 12m/s, power output changes with wind speed by a cube. Tower shadow and turbulence also have an impact on power output in this region.

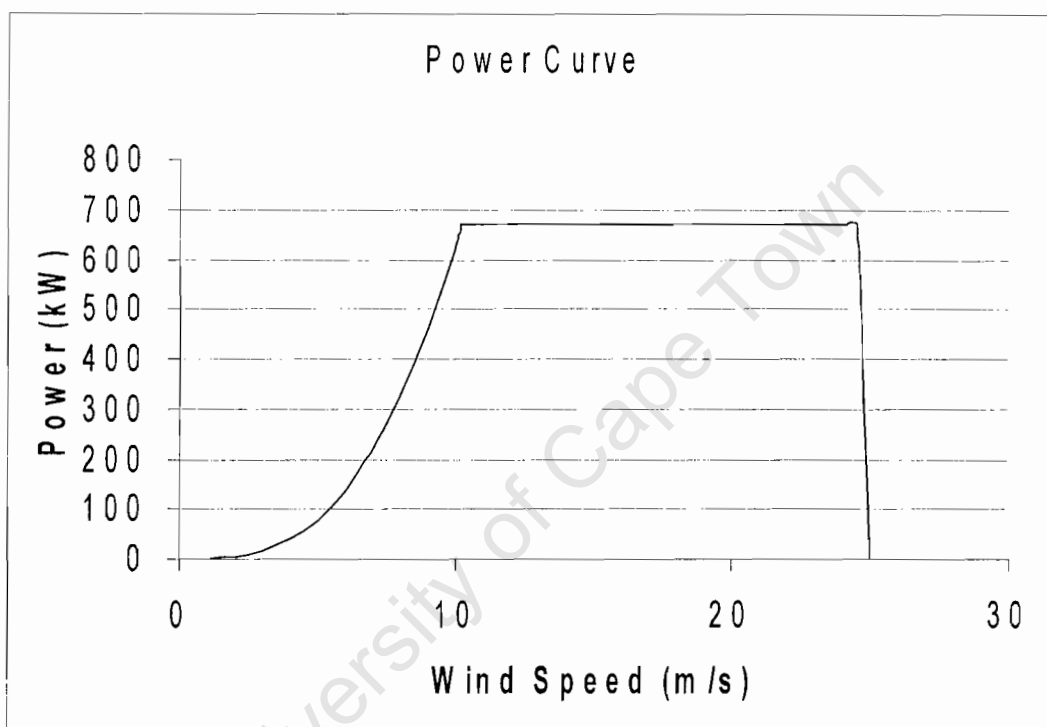


Figure 2. 1 Power Curve [23]

Two main groups of electrical system in wind turbines are found. These are fixed speed wind turbines and variable speed wind turbines. The two types could either use an induction generator or a synchronous generator. Another type of a wind turbine would be a variable wind speed, which uses a synchronous generator with permanent magnets. The latter is usually without a gearbox, meaning generator is designed to connect directly to the grid, via electronic converters. The following section discusses these two electrical systems.

## 2.2.1 Fixed speed wind turbines

Fixed speed wind turbines (FSWT) run at a relatively fixed mechanical speed. These turbines normally employ induction generators that are driven by a turbine via a gearbox and directly connected to the grid. The induction generator runs at an almost constant speed, increasing from the synchronous speed  $n_s$  up to a rated speed which is about 1% higher than the synchronous speed [37]. The application of capacitors compensates for the reactive consumption of the induction generator. The soft starter is also used to limit the inrush current to the induction generator.

Figure 2. 2 is an electrical diagram of a fixed speed wind turbine.

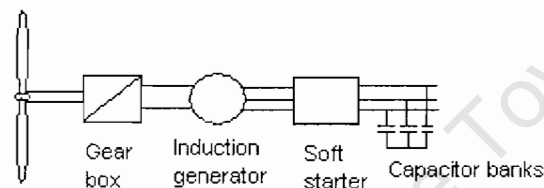


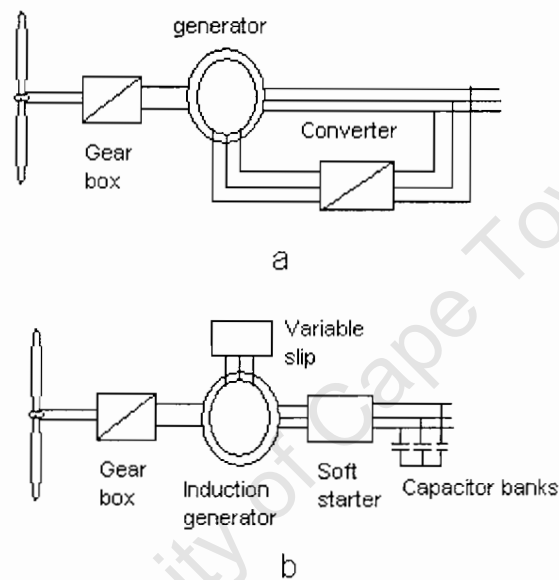
Figure 2. 2 An electrical diagram of a fixed speed wind turbine. [23]

Fixed speed wind turbines produce power fluctuations as depicted by many researchers like Larsson et al [24]. The output power is limited at wind speeds above rated by either pitching the blades or by natural aerodynamic stall before the wind turbine is stopped at cut-out wind speed [37].

## 2.2.2 Variable Speed Wind Turbine

Variable Speed Wind Turbines (VSWT) operate at a variable speed and are usually connected to the grid via power electronic converters. Both synchronous and induction generators could be used in this type of a wind turbine. A direct driven generator could be used where the wind turbine is equipped with a frequency converter. This type of a wind turbine (VSWT) can reduce power fluctuations emanating from the tower shadow.

They operate at either a narrow speed range or a broad speed range. The difference between the two is energy production and the capability of noise reduction [23]. A broad speed range increases the power production and reduces the noise further when compared to a narrow speed range. VSWTs that operate within a narrow speed range are normally equipped with a double-fed induction generator with a converter connected to the rotor as can be seen in Figure 2. 3(a). A narrow speed range wind turbine could also be equipped with controllable rotor resistance. This type of wind turbine is what is known as OptiSlip wind turbines, in which the slip and a speed of the rotor can vary by 1-10% [23].



**Figure 2. 3 Variable Speed Wind Turbine with (a) double-fed induction generator with a converter connected to the rotor and (b) controllable rotor resistance [23]**

A broad speed range wind turbine is equipped with a frequency converter [23]. The use of the latter makes it possible to use a direct-driven generator. The alternating current from the generator is first rectified and then inverted into alternating current before it is fed into the grid. An electrical diagram of a broad-speed range wind turbine is shown below. The converter includes both a rectifier and an inverter.

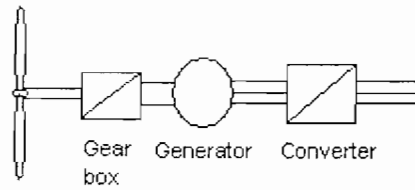


Figure 2. 4 Variable speed wind turbine with a converter [23]

### ***2.3 The connection of wind turbines to the distribution network***

Distribution networks were designed to accept power from the transformers supplied by transmission networks. The flow of real and reactive power has always been from the higher to a lower voltage level [17]. Distribution networks have been passive circuits, supplying the load [17]. However, the connection of wind turbines or any other distributed generator, could change distribution networks from being passive circuits to being active circuits. The flow of real and reactive power could be reversed. Wind turbines export real power and are likely to import reactive power from the grid to magnetise the core of its induction generator [17]. This change in power flow in a distribution system due to the connection of distributed generators has important technical and economic effects for a power system [17]. The technical effects are discussed in section 2.4 of this chapter.

Wind turbines can be stand alone systems or grid connected. Grid connected turbines are usually large wind turbines generating more than 100 kW. It is important to connect the turbine generator to the grid at the right moment once the rotor is rotating at its rated speed. Hence, modern wind turbines connect and disconnect gradually to the grid using thyristors i.e. are soft starting. These thyristors are used to magnetise the machine and to reduce the inrush current during generator start up.

When wind turbines are connected to the grid, voltage fluctuations and stationary voltage variations, which are defined as changes in the RMS value of the voltage occurring in a time span of minutes or more, emanate from the power produced by the turbine [21]. Tower shadow effect and turbulence causes voltage fluctuations.

Tower shadow effects is the effects caused by rotating blades. Every time a blade passes the tower, there is a drop in output power. This drop occurs three times per revolution for a three bladed wind turbine. Wind turbines also affect power quality during the process of connecting the turbines to the grid. Hence, when connecting a wind turbine to the grid, three connection factors are considered. These are [38]:

- Factor stating maximum voltage change during the connection.
- Factor describing the maximum current during the connection and
- Flicker step factor.

The above factors determine how much flicker the wind turbine emits during switching operations.

The following section describes the effect that distributed generators have on power quality of distribution networks, followed by a section on power quality of wind turbines.

## ***2.4 The effects of wind turbines on power quality***

As mentioned before, wind turbines are said to be good examples of generators that cause voltage flicker [17]. This is due to the fluctuating power output produced by wind turbines. Power fluctuations are caused by variable wind speed, tower shadow and mechanical properties of the wind turbine. Hence the studies on power quality of wind turbines are discussed in this report. Section 2.4.1 explains voltage flicker and why it is of great concern when wind turbines are connected to the grid.

### ***2.4.1 Voltage flicker***

Voltage flicker is the measure of voltage variations, which may cause disturbances to consumers [20]. According to Jenkins et al [17], voltage flicker describes dynamic variations in the network voltage, which may be caused either by

distributed generators or by loads. The term voltage flicker originates from the effects of the voltage fluctuation on the brightness of the incandescent lights [17]. It has been shown that the eye is most sensitive to voltage variations around 10 Hz. The following curve, Figure 2. 5, indicates the magnitude of sinusoidal voltage changes, which have been shown to be perceptible to observers, according to IEC 868. [37].

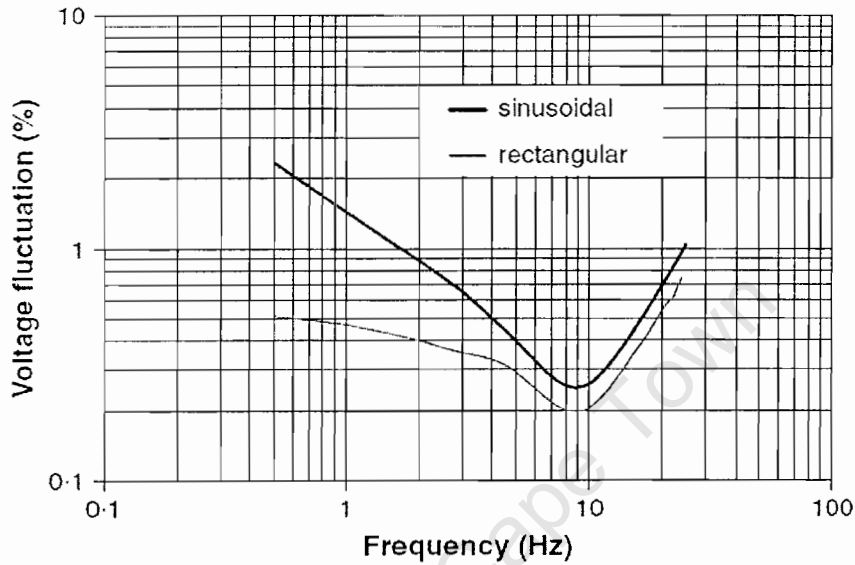


Figure 2. 5 Normalised flicker response for voltage fluctuations [37]

Flicker is said to be of considerable significance for distributed generators which:

- (i) often uses relatively large individual items of plant compared to load equipment;
- (ii) may start and stop frequently;
- (iii) may be subject to continuous variations in input power from a fluctuating energy source [17]

Since wind turbines are mentioned as being one of the generators that could result in voltage flicker, flicker emission by wind turbines is then studied in detail.

Voltage flicker is usually evaluated over a 10 minute period to give a short term severity value;  $P_{st}$ .  $P_{st}$  is measured using a flickermeter that complies with the requirements of IEC 868 [28]. A long-term severity value,  $P_{lt}$ , is obtained by combining twelve  $P_{st}$  values using the following equation:

$$P_{lt} = \sqrt[3]{\frac{\sum_{k=1}^{12} P_{st,k}^3}{12}} \dots\dots\dots(2.4)$$

$P_{lt}$  is calculated over a 2-hour period.

According to NRS 048-2 [30], the compatibility level for short-term flicker severity  $P_{st}$  and long-term flicker severity  $P_{lt}$  are 1.0 and 0.8 respectively.

Wind turbines produce flicker during continuous operations due to power fluctuations. These power fluctuations are the result of variations in wind speed, the tower shadow effect and mechanical properties of the wind turbine. However, flicker may also occur during switching operations. Flicker during switching operations is due to voltage changes during stop and start of a wind turbine. The following two sections discuss flicker during switching and continuous operations respectively.

**(a) Flicker during switching operations of wind turbines**

Switching operations cause voltage flicker [20]. These switching operations are the start and stop of a wind turbine. Start and stop of a wind turbine will cause a change in power production. This change in power production causes voltage changes at the point of common connection (PCC) [20]. These voltage changes will then cause flicker.

Starting operation differs for each wind turbine type. This means that variable speed wind turbines start differently from fixed speed wind turbines. In a fixed speed wind turbine, the speed is raised during the starting sequence until the generator speed is close to the synchronous speed. Once this is done, the generator is then connected to the grid. Stall regulated wind turbines give a higher in-rush current while pitch regulated wind turbines can control the torque of the turbine, resulting in low in-rush current.

The influence of wind turbines on the grid during switching operations can be classified as: [39]

- i. The first case is the impact on steady state voltage level during the turbine generator connection. The turbine generator draws high currents, resulting in voltage dips
- ii. The second case is due to capacitor switching. Capacitors are situated in the nacelle. They are used for reactive power compensation. The capacitor bank is connected immediately after the generator is connected to the grid. The connection of the capacitor bank causes a large current peak, which affects the voltage of the grid where the wind turbine is connected.

However, both switching cases give rise to high flicker values. Flicker due to switching operations has different limits compared to flicker during continuous operations.

Flicker during switching operations is assessed assuming that each wind turbine is characterised by a flicker step factor  $k_f(\Psi_k)$ . It is determined using the following equations: [37]

$$P_{st} = 18 \times N_{10}^{0.31} \times k_f(\Psi_k) \times \frac{S_n}{S_k} \dots\dots\dots(2.5)$$

and summed using equation (2.6)

$$P_{st} = \frac{18}{S_k} \left( \sum_{i=1}^{N_{wt}} N_{10,i} (k_{f,i}(\Psi_k) S_{n,i})^{3.2} \right)^{0.31} \dots\dots\dots(2.6)$$

Where  $S_k$  is the short circuit apparent power (VA),  
 $N_{10}$  is the number of switching operations within 10 min,  
 $k_f(\Psi_k)$  is the flicker step factor of the wind turbine for the given network impedance phase angle,  $\Psi_k$ , at the point of common connection (PCC),  
 $S_n$  is the rated apparent power of the individual wind turbine and  
 $N_{wt}$  is the number of wind turbines connected to the PCC.

The above flicker equations may be deduced by observing the definition of the flicker step factor given in [28]:

$$k_f(\psi_k) = \frac{S_{k, fic}}{100S_n} P_{st, fic} \left( \frac{T_p}{2.3} \right)^{1/3.2} \dots\dots\dots(2.7)$$

Where  $T_p$  is an observation period

For an observation period of 600s, which corresponds to a short term flicker period and replacing the fictitious grid characteristic with an actual  $S_k$  and  $P_{st}$ , the following equation for a single  $P_{st}$  is deduced:

$$P_{st} = 18k_f(\psi_k) \frac{S_n}{S_k} \dots\dots\dots(2.8)$$

**(b) Flicker during continuous operation**

Flicker emission during continuous operations is caused by variations in the power produced by wind turbines. Tower-shadow effects result in output power variations, which in turn cause voltage fluctuations, which cause flicker. This is because every time the blade passes the tower, there is a power drop as none of the blades are at a highest point where wind speed is at maximum. However, when one of the blades is at the highest point, the turbine produces maximum power as none of the blades is at the lowest point.

The procedure for assessing flicker emission due to continuous operation assumes that each wind turbine is characterised by a flicker coefficient  $c(\Psi_k, v_a)$ , which is a measure of the maximum expected flicker emission during continuous operation of the wind turbine.

The flicker coefficient is given by the equation: [28]

$$c(\psi_k, v_a) = P_{st, fic} \frac{S_{k, fic}}{S_n} \dots\dots\dots(2.9)$$

Replacing the fictitious grid characteristics with the actual  $S_k$  and  $P_{st}$ , and using a general formula for flicker summation,

$$P_{st} = \left( \sum_i P_{st,i}^m \right)^{1/m} \dots\dots\dots(2.10)$$

the flicker severity due to a wind farm with  $N_{wt}$  wind turbines is given by:

$$P_{st} = \frac{1}{S_k} \left( \sum_{i=1}^{N_{wt}} (c_i (\psi_k, v_a) S_{n,i})^m \right)^{1/m} \dots\dots\dots(2.11)$$

where  $m$  is assumed to be 2 [28].

## 2.5 Summary

This chapter has introduced distributed generation, as well as wind turbines as one of the distributed generation technologies. A definition for DG's is explained. Wind Turbine design is explained, and how wind is converted to electrical energy. Wind turbines are categorised into two electrical systems, fixed speed wind turbines (FSWTs) and variable speed wind turbines (VSWTs). FSWTs operate at a relatively fixed speed while VSWTs can start operating at relatively low wind speeds.

The connection of wind turbines to the grid could affect the power quality of that particular distribution network. Because wind turbines have a variable source of power, wind, the output power produced fluctuates, depending on the wind speed. This dependency of wind turbine power output on the wind speed is shown by the equation  $P = \frac{1}{2} C_p \rho V^3 A$ .

Wind turbines are said to emit flicker, especially when connected to distribution networks. Flicker is emitted during both switching and continuous operations. Flicker emission during switching conditions is as a result of the starting and stopping of a wind turbine. Start and stop of a wind turbine will cause a change in power production, which results in flicker. Flicker emission during continuous

operations is caused by variations in the power produced by wind turbines. Tower-shadow effects result in output power variations, which in turn cause voltage fluctuations, which cause flicker.

Three wind turbines are installed in South Africa and the studies presented in this report were conducted on this wind farm. The next chapter is an introduction to the South African wind farm, Klipheuwel wind farm, as well as distribution network where this wind farm is connected.

University of Cape Town

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## 3. FUNCTIONAL DETAILS OF WIND TURBINES AND BACKGROUND TO A SOUTH AFRICAN WIND FARM

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The first wind farm was established in South Africa in 2002/2003. Eskom carried out an investigation on wind energy as one of the resources to make electricity. South Africa was reported to have a more moderate wind resource along the coastline [34]. However, after the environmental impact assessment was conducted on 10 sites, a decision was made to choose Klipheuwel as a preferred site for the first wind farm in South Africa.

In this chapter, a background on this South African wind farm is discussed. Detailed technical information of the installed wind turbines is also explained. South African distribution networks are also discussed as these play an important role on studies of power quality of grid connected wind turbines.

### **3.1 Klipheuwel Wind Farm**

Three wind turbines have been installed in South Africa in the Klipheuwel wind farm, about 50km from Cape Town. The wind farm is a pilot project that will run for about three years to test the feasibility of wind energy in South Africa [7] from 2003. One of the aspects that give direction for the wind energy research are power quality and local effect of wind turbines on grid [34]. Hence the study on power quality impact of wind turbines on distribution networks.

The first wind turbine, a 660kW Vestas V47 unit, was installed in 2002. This wind turbine was imported from a Danish company, Vestas. The turbine has an induction generator, with a rated fixed synchronous speed of 1,515 – 1,650 rpm. It is fitted with OptiSlip, which allows the generator and the rotor to vary their speed by up to

10% to cope with the violent gusts of wind [44]. This turbine is of a fixed speed type. V47 is equipped with microprocessor controlled OptiTip pitch regulation, which ensures continuous and optimal adjustment of the angle of the blades in relation to the prevailing wind. See Table 3. 1 for more on technical data of the turbine V47

Table 3. 1 Vestas V47 Wind Turbine Data

<b>Unit</b>	<b>Vestas V47</b>
<b>Rated Power</b>	<b>660 kW</b>
<b>Rotor</b>	
<b>Diameter</b>	47 m
<b>Blade Number x Length</b>	3 x 23 m
<b>Swept area</b>	1 735 m <sup>2</sup>
<b>Speed revolution</b>	28.5 rpm
<b>Operational interval</b>	28.5 - 30 rpm
	252.5 - 265.8 km/h
<b>Rotor orientation</b>	Horizontal, face wind
<b>Power regulation</b>	Pitch/OptiSlip®
<b>Tower</b>	
<b>Hub height (approx)</b>	40 m
<b>Operational data</b>	
<b>Cut-in wind speed</b>	4 m/s (self start at average wind speed of ~4.5 m/s)
<b>Nominal wind speed</b>	15 m/s (54 km/h)
<b>Stop wind speed</b>	25 m/s (90 km/h)
<b>Generator</b>	
<b>Type</b>	Asynchronous/Induction Generator (radial flux cylindrical) with OptiSlip®
<b>Nominal output</b>	660 kW
<b>Operational data</b>	50 Hz; 690 V
<b>Synchronous speed</b>	1,515 - 1,650 rpm

The second wind turbine, a 1.75 MW Vestas V66 unit, was erected in 2002. This wind turbine is of a variable speed type, with an induction generator. This means that the turbine needs reactive power from the grid to magnetise the generator. The variable speed has an advantage that this machine will start up even at lower wind speeds. Table 3.2 shows some technical information on this turbine. The swept area of the rotor, which is used when calculating power produced, is also shown in this table.

**Table 3.2 Vestas V66 Wind Turbine Data**

<b>Unit</b>	<b>Vestas V66</b>
<b>Rated Power</b>	<b>1.75 MW</b>
<b>Rotor</b>	
<b>Diameter</b>	66 m
<b>Blade Number x Length</b>	3 x 32 m
<b>Swept area</b>	3 421 m <sup>2</sup>
<b>Speed revolution</b>	21.3 rpm
<b>Operational interval</b>	10.5 - 24.5 rpm
<b>Tip speed</b>	130.6 – 265 – 305 km/h
<b>Rotor orientation</b>	Horizontal, face wind
<b>Power regulation</b>	Pitch/OptiSpeed™
<b>Hub height (approx)</b>	60 m
<b>Operational data</b>	
<b>Cut-in wind speed</b>	4 m/s (14.4 km/h) Self start
<b>Nominal wind speed</b>	16 m/s (57.6 km/h)
<b>Stop wind speed</b>	25 m/s (90 km/h)
<b>Generator</b>	
<b>Type</b>	Asynchronous/Induction Generator (radial flux cylindrical) with OptiSpeed™
<b>Nominal output</b>	1750 kW
<b>Operational data</b>	50 Hz; 690 V

The third wind turbine was commissioned in 2003, with a rated power of 750 kW. It is a variable speed wind turbine, which uses a synchronous generator with permanent magnets, meaning it does not have a gearbox and uses power electronics to regulate voltage. It is a direct drive machine. This turbine, J48, is a French import, from Jeumont Company. Its generator is designed for grid connection through an electronic converter AC/DC/AC [1].

**Table 3. 3 Jeumont J48 Wind Turbine Data**

<b>Unit</b>	<b>Jeumont J48</b>
<b>Rated Power</b>	<b>750 kW</b>
<b>Rotor</b>	
<b>Diameter</b>	48 m
<b>Blade Number x Length</b>	3 x 23 m
<b>Swept area</b>	1 810 m <sup>2</sup>
<b>Speed revolution</b>	Variable
<b>Operational interval</b>	7-26 rpm
<b>Rotor orientation</b>	Horizontal, face wind
<b>Power regulation</b>	Stall Aerodynamic uncoupling
<b>Hub height (approx)</b>	46 m
<b>Operational data</b>	
<b>Cut-in wind speed</b>	3 m/s (10.8 km/h)
<b>Nominal wind speed</b>	13.5 m/s (48.6 km/h)
<b>Stop wind speed</b>	25 m/s (90 km/h)
<b>Generator</b>	
<b>Type</b>	Synchronous generator with permanent magnets, (axial flux discoidal) with IGBT electronic converter with vectorial control system
<b>Nominal output</b>	750 kW
<b>Operational data</b>	50 Hz; 690 V (Grid)
<b>Synchronous speed</b>	900 V (Gen)

The following picture, Figure 3. 1 shows the three wind turbines in Klipheuwel, and the picture was taken on top of V66. The furthest wind turbine is the Jeumont J48. The photo in Figure 3. 2 was taken inside a nacelle of V66 wind turbine. This shows how big the nacelle is for this particular wind turbine.



Figure 3. 1 South African wind farm, Klipheuwel



Figure 3. 2 Inside V66 Nacelle, with generator at the background

These three turbines are connected to an 11 kV busbar. They each generate 690V and this voltage is transmitted to the grid via a 0.69/11 kV transformer. Each wind turbine has its own 0.69/11 kV transformer. For V66, the transformer is situated in the nacelle, as the latter is big enough to accommodate it. However, for the other two turbines, each has its' own 0.69/11 kV transformer situated outside the tower. The combined generated power from the three turbines is then sent to the Klipheuwel substation via an 11kV cable.

### ***3.2 The connection of Klipheuwel wind farm to the Eskom grid***

Klipheuwel wind farm is connected to an 11kV distribution network. The following diagram, **Error! Reference source not found.** shows the connection of the wind farm to the Eskom distribution network.

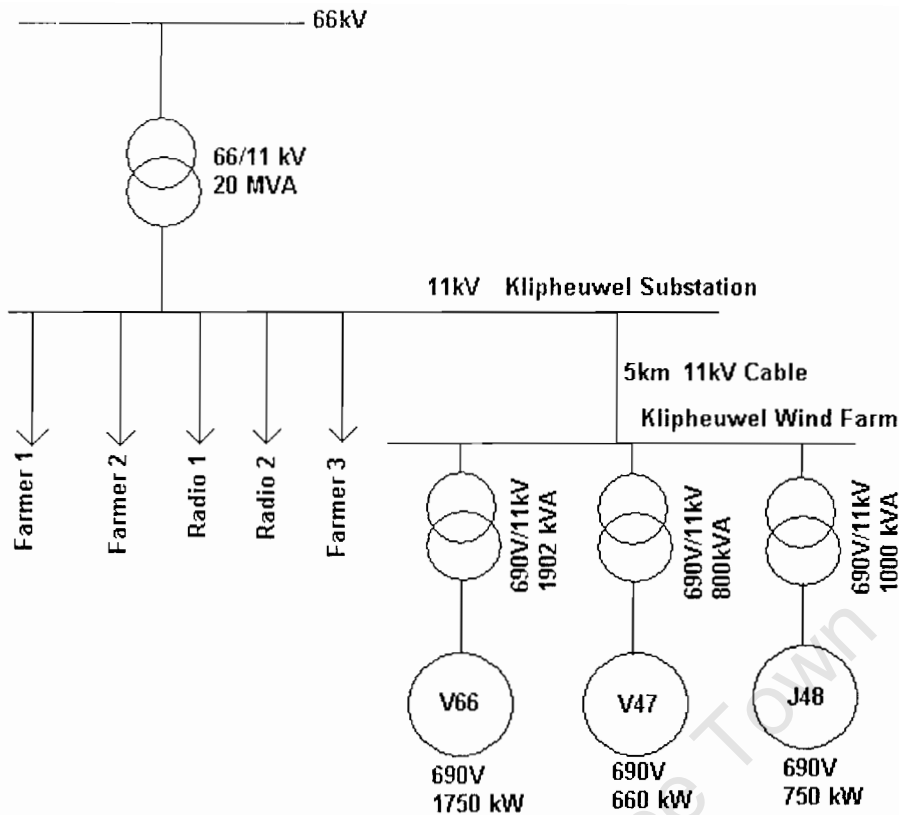


Figure 3. 3 Grid Connection of Klipheuwel wind farm

The above diagram indicates the connection of wind turbines to an 11kV substation, Klipheuwel. The three wind generators connected to the wind farm bus bar represent wind turbines V66, V47 and J48 respectively. These generators are each connected to a 690V/11kV transformer, and feed to Klipheuwel 11kV substation, where other loads are connected. Klipheuwel wind farm is connected to the substation via a PILC 11kV cable, 5km long. The short circuit capacity on the low voltage side of the 690V/11 kV is 1902kVA, 800kVA and 1000kVA for wind turbine V66, V47 and J48 respectively.

### 3.3 Distribution Networks in South Africa

Distribution networks are generally designed to accept bulk power supply from transmission lines and distribute it to customers. The flow of power would therefore be from higher voltage to lower. However, with distributed generators connected to

the network, the power flow could be reversed. This has a significant effect to the power quality of distribution networks.

Two types of distribution networks can be found in Southern Africa. These include radial distribution networks and ring distribution networks. Studies carried out in this report are done on a radial distribution network. Hence this network is explained more below. South African distribution networks are defined to operate at a voltage less or equal to 132kV.

The majority of South African distribution networks in rural areas are constrained by voltage-related issues rather than capacity or waveform quality [40]. South African distribution networks are defined as weak distribution networks. The characteristics of a weak network include a very low X/R ratio, which results to relatively high impedance of the distribution lines. The distributed nature of network load indicates that rural distribution feeders are long, and have relatively small HV/MV transformer capacities (from 750kVA) [40].

Changes in both active and reactive power have an impact on steady state voltage changes. These networks experience voltage fluctuations, especially after a disturbance on the network. For this reason, steady state voltage fluctuation and flicker are to be studied when connecting wind turbines. Also, an increase in grid strength affects the flicker emission by wind turbines, hence short circuit capacity of the grid is to be considered for flicker emission studies.

### **3. 4 Summary**

In this chapter, the background to Klipheuwel wind farm was discussed. One of the aspects, which give direction to wind energy research in South Africa, is power quality and local effect of wind turbines on the grid. Hence the studies on power quality in this thesis.

Three wind turbines are installed in Klipheuwel wind farm, with a total capacity of 3.16MW. These wind turbines are of different types; hence power quality studies on

each of them are expected to be different. The first wind turbine is a 660kW Vestas V47 unit. The turbine has an induction generator, with a rated fixed synchronous speed of 1,515 – 1,650 rpm. This turbine is of a fixed speed type. V47 is equipped with microprocessor controlled OptiTip pitch regulation, which ensures continuous and optimal adjustment of the angle of the blades in relation to the prevailing wind.

The second wind turbine is also a Vestas machine, with a capacity of 1.75MW, and is called V66. This wind turbine is of a variable speed type, with an induction generator. This means that the turbine needs reactive power from the grid to magnetise the generator. The variable speed has an advantage that this machine will start up even at lower wind speeds.

The third wind turbine is from a French company, Jeumont, with a rated power of 750 kW. It is a variable speed wind turbine, which uses a synchronous generator with permanent magnets. This means that it does not have a gearbox and uses power electronics to regulate voltage. It is a direct drive machine. Its generator is designed for grid connection through an electronic converter AC/DC/AC [1].

Klipheuwel wind farm is connected to an 11kV distribution network. However, South African distribution networks are considered as weak networks, due to, among other reasons, high line impedance as a result of long lines, and small HV/MV transformers. This weak nature of distribution network results to studies on power quality as grid connected wind turbines could affect it.

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## 4. THEORETICAL ASPECTS OF POWER QUALITY

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The connection of wind turbines to distribution networks could have an impact on power quality of that particular network as mentioned in the previous chapters.

In this chapter, the meaning of power quality is described as well as the physical characteristics and properties of electricity that describe power quality. It carries on describing the theoretical aspects of power quality and the effects that wind turbines could have on power quality.

### **4.1 Definition of Power Quality**

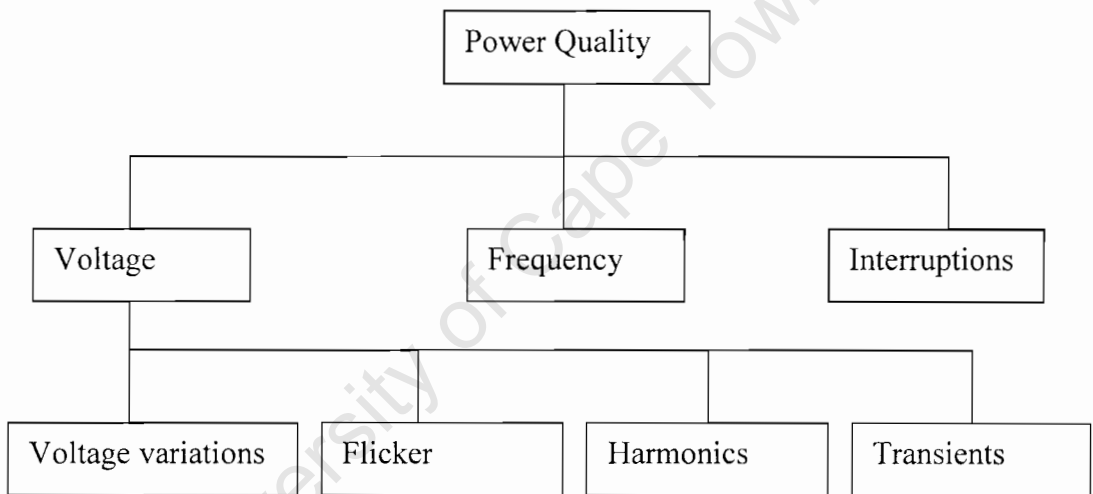
IEC standards refer to power quality as electromagnetic compatibility, defined as “the ability of an equipment or system to function satisfactory on its electromagnetic environment without introducing intolerable electromagnetic disturbances to anything in that environment” [15]. Alternatively, IEEE defines power quality as “the concept of powering and grounding sensitive equipment in a matter that is suitable to the operation of that equipment” [15]. NRS 048-1[30] describes quality of supply as “technical parameters to describe the electricity supplied to customers, and that are used to determine the extent to which the needs of customers are met in the utilisation of electricity.”

Perfect power quality means that the voltage is continuous and sinusoidal, having a constant amplitude and frequency [23]. However, due to some factors that affect the electricity networks, perfect power quality with continuous and sinusoidal voltage can hardly be achieved.

Different standards are then used, differing from country to country, describing the acceptable power quality in that particular country.

Power quality is mostly described in terms of voltage disturbances, frequency and interruptions.

Figure 4. 1 shows the classification of power quality [23]. However, not all the characteristics of power quality are presented in the chart. A lot of attention will however be focussed on voltage disturbances, as these are the forms of power quality identified by the literature survey to be the main concern when wind turbines are grid connected.



**Figure 4. 1 Classification of different power quality phenomena [23]**

## ***4.2 The characteristics of Power Quality***

The following are the measurable quantities or occurrences of power quality [17, 36].

### **4.2.1 Voltage Dip**

Voltage Dip is the reduction in the RMS voltage, for a period of between 20 ms and 3 seconds [30]. The duration of a voltage dip is the time measured from the moment the RMS voltage drops below 0.9 per unit of declared voltage to when the voltage rises above 0.9 per unit of declared voltage [30]. Voltage dip is usually caused by faults on the transmission or distribution networks, increased load demand and transitional events such as large motor starting. It is said that start-up of a wind turbine can cause sudden reduction of the voltage [37]. However, voltage dips are not a constraint for further expansion of wind farms.

#### 4.2.2 A transient

A transient is an undesirable momentary deviation of the supply voltage or load current. Transients could occur mainly during the start and shut down of a fixed speed wind turbine. A transient could sometimes reach a value of twice the rated wind turbine current, which could affect the voltage of a low-voltage grid [23]. This voltage transient can disturb sensitive equipment connected to the same grid [23]. The impedance of the grid and the capacitance of the capacitor determine the amplitude of the current emanating from the switching of an unloaded capacitor. The frequency of the transient is given by the following equation.

$$f = \frac{1}{2\pi} \sqrt{\frac{1}{LC}} \dots\dots\dots(4.1)$$

Where L is the inductance of the grid and C is the capacitance of the capacitor. The capacitance C is that of a shunt capacitor bank connected inside a nacelle, used to magnetise an induction generator

#### 4.2.3 Harmonics

Harmonics are periodic sinusoidal distortions of the supply voltage or load current caused by non-linear loads, power electronic loads, rectifiers and inverters in motor drives etc. The effects of harmonics include overheating and equipment failure, faulty operation of protective equipment, tripping of sensitive loads and interference with communication circuits. Harmonics are measured in integer multiples of the

fundamental supply frequency, i.e., 100Hz, 150 Hz, 200Hz, 250Hz, etc. Variable speed wind turbines are said to generate harmonics while fixed speed wind turbines are not expected to cause significant harmonics.

#### **4.2.4 Voltage flicker**

Voltage flicker is the visual effect of small voltage variation on electrical lighting equipment. It may be caused by either distributed generators or by loads. Wind turbines are said to be one of the generators that contribute voltage flicker on distribution networks, resulting to the power quality being degraded. This phenomenon is described in more details in section 4.4 of this chapter.

#### **4.2.5 Frequency deviation**

It is the variation in frequency from the nominal supply frequency above or below the predetermined level, normally  $\pm 0.1\%$ . This is considered in an autonomous grid, as the spinning reserve is smaller in autonomous grids supplied by diesel engines.

### **4.3 Power Quality of Wind Turbines**

Grid-connected wind turbines are said to affect the power quality of the grid where they are connected [23]. However, when it comes to the operation of wind turbines, not all the power quality characteristics are affected. When the wind turbines produce power, voltage variations occur [23]. All wind turbines are hence said to cause voltage variation as they produce variable energy. Load flow calculations and other methods are used to calculate voltage variation. According to Gardner [8], there are three main issues that affect the power quality of wind turbines. These are harmonics, flicker and voltage steps. However, voltage flicker has been the main issue that affects the power quality of wind turbines due to power fluctuations that the turbines produce. For this reason, studies have been carried specifically on flicker emission by wind turbines. The following chapter explains voltage flicker, from its definition, to how it affects the power quality of the distribution networks

where wind turbines are connected. Also explained in the next chapter are ways on how to measure power quality of wind turbines according to IEC 61400-21 [28].

Fixed speed wind turbines are said to have a higher flicker emission as they have a high flicker coefficient  $C(\psi_k)$ . Variable speed wind turbines have power electronic converters; and are hence said to have less impact on flicker. However, the power electronics could results to harmonics being induced into the network.

Steady state voltage fluctuations and flicker emissions are discussed below as the main power quality issues that affect the connection of wind turbines.

### 4.3.1 Steady State Voltage Fluctuations

Operation of wind turbines may affect the steady state voltage of the connected network [3]. Steady state voltage fluctuations are measured using the following two-node system

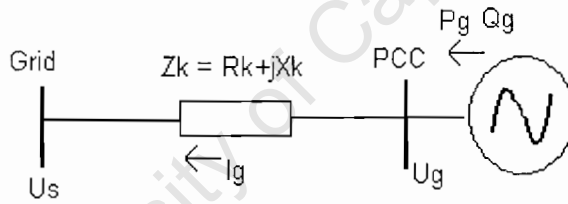


Figure 4. 2 Simple Impedance Model [3]

This system illustrates a wind farm connected to a network with equivalent short circuit impedance  $Z_k$ .  $U_s$  is the voltage at an infinite busbar while PCC is a Point of Common Coupling, where wind turbine generators are connected.

The current generated by the wind turbines is given by the following equation;

$$I_g = \left( \frac{S_g}{U_g} \right)^* \dots\dots\dots(4.3)$$

Where

$$S_g^* = P_g - jQ_g \dots\dots\dots(4.4)$$

Therefore, the voltage difference  $\Delta V$  is given by the following equation

$$U_g - U_s = Z_k * I_g = (R_k + jX_k) \left( \frac{P_g - jQ_g}{U_g} \right) \dots\dots\dots(4.5)$$

From the equation above, it can be seen that voltage difference is related to short circuit impedance  $Z_k$ , the real and reactive power output of the wind turbines,  $P_g$  and  $Q_g$  respectively. Hence any change on power generated by the wind turbines would result to variations of the voltage at PCC. The voltage difference could be calculated using load flow analysis methods, with the wind turbine node assumed to be a PQ node. These calculations are done and explained in chapter 5.

The voltage level impact on the grid with fixed speed wind turbines depends mainly on the grid X/R ratio and a smaller extent on the induction generator characteristics [39].

Voltage fluctuations are caused mainly by tower shadow effect. Every time a blade passes a tower, power output is reduced. For a three bladed wind turbine, the power drop will appear three times per revolution of the turbine.

### 4.3.2 Flicker Emission or Dynamic Voltage Fluctuations

The turbulence in the wind together with the wind turbine itself creates power variations in the region of 0.01 – 10 Hz [39]. However, the use of power electronic converters in wind turbine system provides the possibility to reduce the dynamic voltage fluctuations [39]. The reactive power can be controlled to minimise the voltage fluctuations and the turbine rotor speed could also be changed.

Nevertheless, fluctuations in the system voltage could result in perceptible light flicker, depending on the magnitude and frequency of the fluctuation [3]. Rapid variations in power output of a wind turbine, such as generator switching and capacitor switching can also result in variations in the RMS value of the voltage.

Hence this section defines flicker emission, what causes it and how to measure flicker emission from wind turbines, from a theoretical point of view.

### **What is Flicker?**

Larsson [23] defines flicker as a measure of voltage variations, which may cause disturbances to customers. Flicker is also referred to as short lived voltage fluctuations, which result in a light bulb to flicker and can be detected by the human eye. These voltage fluctuations occur at frequencies below and equal to 10Hz. This is the frequency region where a human eye is sensitive. The magnitude of maximum permissible voltage change with respect to the number of voltage changes per second as shown in figure 2.3.

Flickermeter is used to measure flicker. The method is based on measurements of variations in the voltage magnitude. The flickermeter architecture is divided into two parts, each performing one of the following tasks: [28, 21]

- Simulation of the response of the lamp-eye-brain chain, which is weighted by two different filters, one corresponds to the response of a 60W light bulb and the other to the response of the human eye and brain to variations in the luminance of the light bulb.
- On-line statistical analysis of the flicker signal and presentation of the results.

However, flicker from wind turbines is not determined from voltage measurements alone, as the background flicker of the grid could influence this method [28].

Different methods have been used by many researchers in countries such as Germany, Denmark, Sweden and many others, mainly in Europe. These methods are defined below.

- Active and reactive power measurements. The measured power is used as an input to flicker algorithm, which is programmed according to IEC 61000-4-

15.  $P_{st}$  values are then obtained from this algorithm and flicker analysis can be carried through. Power could be measured either as a 10-minute average data ( $P_{mc}$  and  $Q_{mc}$ ), 60s average data ( $P_{60}$  and  $Q_{60}$ ) or 0.2 second average data ( $P_{0.2}$  and  $Q_{0.2}$ ), using power transducers. P60 and P0.2 are maximum measured power values. This method was not used at Klipheuwel wind farm as it required power transducers as well as voltage and current transformers.

- Voltage and Current measurements. Instantaneous current measurements are used to compute voltage, which is used as an input to flicker algorithm. A fictitious grid is used as shown in Figure 4.3. The voltage and current measurement method was used at Klipheuwel wind farm, where only voltage test set and current transformers were used. Flicker values were then determined directly from measured voltage and current time-series

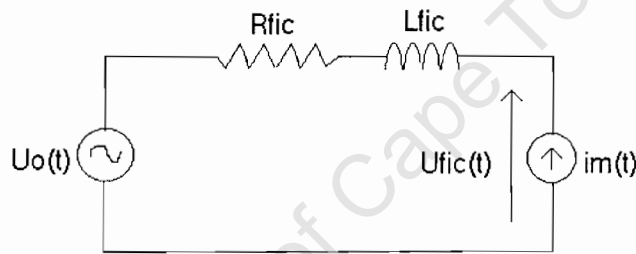


Figure 4. 3 Fictitious grid for calculating flicker [28]

Where

$i_m(t)$  represents the wind turbine,

$R_{fic}$  and  $L_{fic}$  represent the resistance and inductance of the fictitious grid respectively

$U_0(t)$  is an ideal voltage source.

The following equation is used to obtain the required values of the input voltage

$U_{fic}(t)$  [28]

$$u_{fic}(t) = u_0(t) + R_{fic}(t) \cdot i_m(t) + L_{fic}(t) \cdot \frac{di_m(t)}{dt} \dots\dots\dots(4.6)$$

$L_{fic}$  and  $R_{fic}$  are selected to obtain the appropriate network impedance phase angle  $\Psi_k$

applying the following equation:

$$\tan(\Psi_k) = \frac{X_{fic}}{R_{fic}} \dots\dots\dots(4.7)$$

$30^0$ ,  $50^0$ ,  $75^0$  and  $85^0$  are the values of  $\Psi_k$  that are usually used, according to IEC 61400-21 [28].

The following block diagram illustrates the above method for determining flicker from wind turbine during continuous operation.

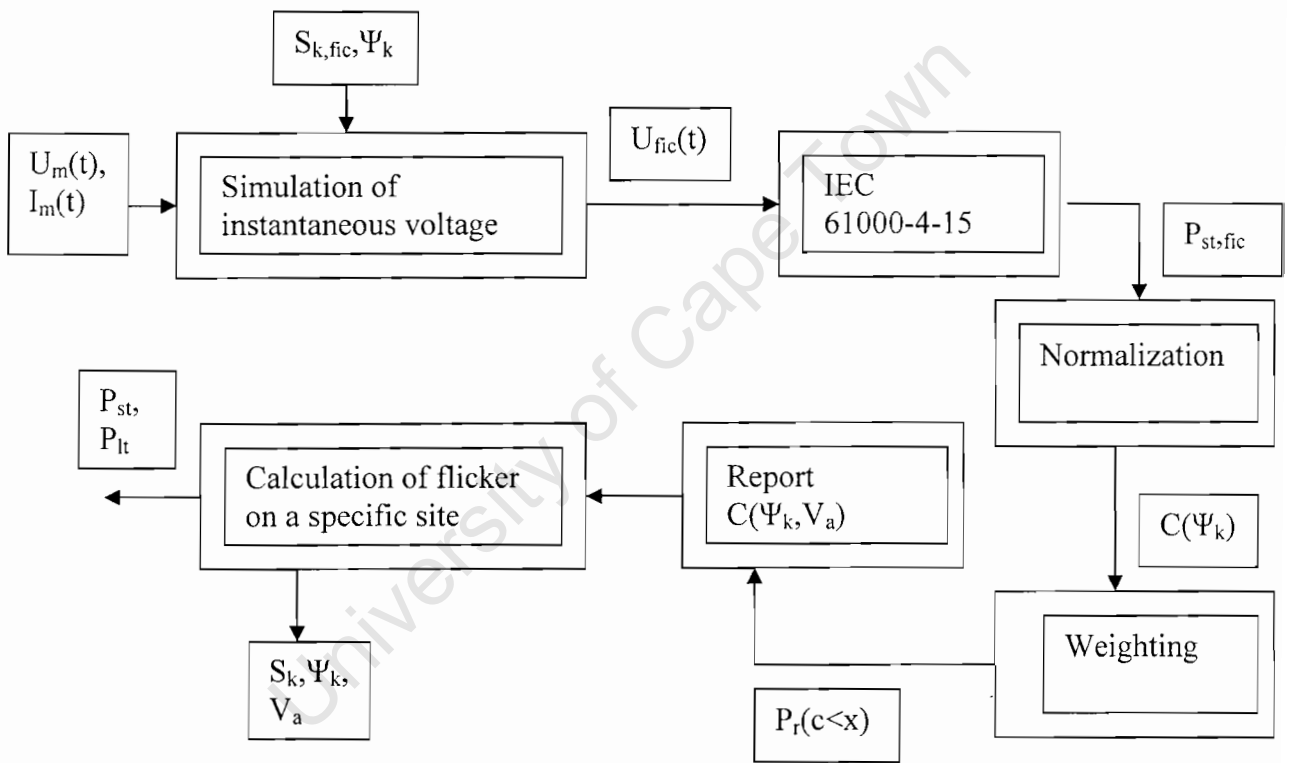


Figure 4. 4 Flicker Calculations [28]

The above methods used to measure flicker are based on the fact that the flickering of the light bulb irritates people. This level of irritation is classified by a dimensionless quantity,  $P_{st}$  over a 10-minute period.  $P_{st} = 1$  means that the majority of people are irritated. This flicker index,  $P_{st}$ , can reach high values, due to other power quality characteristics such as transients,

The acceptable value of  $P_{st}$  varies from country to country, for instance in South Africa, the compatibility level for  $P_{st}$  is 1, and for a long-term flicker  $P_{lt}$  is 0.8.

University of Cape Town

### Flicker Calculation and Summation during continuous operation:

Flicker is calculated in terms of flicker coefficient and short circuit ratio using the following formula:

$$P_{st} = c(\Psi_k) \frac{S_{ref}}{S_k} \dots \dots \dots (4.8)$$

Where  $S_{ref}$  refers to the wind turbine's rated power,

$S_k$  is the grid short circuit capacity

$c$  is the flicker coefficient of that particular wind turbine.

$P_{lt}$  is a long-term severity flicker. It is calculated over a 2-hour period by combining twelve  $P_{st}$  values as shown in the equation below.

$$P_{lt} = \sqrt[3]{\frac{\sum_{k=1}^{12} P_{st,k}^3}{12}} \dots \dots \dots (4.9)$$

Flicker summation can be done in two different ways:

- It could be summed as a square root of the sum of the squared flicker values as can be seen in the formula below:

$$P_{st\Sigma} = \sqrt{\sum_i P_{st,i}^2} \dots \dots \dots (4.10)$$

Where  $P_{st,i}$  is the flicker emission from each individual wind turbine as shown above, hence this equation could be rewritten as below:

$$P_{st\Sigma} = \frac{1}{S_k} \sqrt{\sum_{i=1}^{N_{wt}} (c_{f,i}(\Psi_k, v_a) S_{n,i})^2} \dots \dots \dots (4.11)$$

$c_{f,i}(\Psi_k, v_a)$  is the flicker coefficient of the individual wind turbine;

$S_{n,i}$  is the rated apparent power of the individual wind turbine;

$N_{wt}$  is the number of wind turbines connected to the PCC.

#### **4.5 Factors that Affect Flicker Emission from Wind turbines**

- (a) The grid strength – this is the ratio between the grid short circuit capacity and the rating of wind turbine, ( $S_k/S_{ref}$ ).

An increase in grid strength results to reduced flicker emission by wind turbines [39].

- (b) The grid impedance ratio (X/R ratio). An X/R ratio of 1 corresponds to a grid impedance angle of  $45^\circ$ .

- (c) Turbulence intensity - Flicker increases with an increase in wind speed due to higher turbulence in the wind. The turbulence in the wind creates power variations in the region of 0.01 -10 Hz [37]. These power variations results to high flicker emission.

- (d) Tower shadow effect – there is a power drop every time a blade passes the tower. This reduces the power 3 times per revolution. The frequency of the power pulsations is equal to the number of blades multiplied by the rotational speed of the turbine. For instance, the expected frequency of the power pulsation for the wind turbine V47 is 1.425 Hz. This is calculated from the given rotational speed of the rotor (28.5 rpm), multiplied by the number of blades (3), then divide by 60 to get frequency in hertz. The power pulsations results in flicker emissions.

#### **4.5 Summary**

Power quality is perfect when the voltage is sinusoidal and continuous, having a constant amplitude and frequency. However, due to other factors that affect an electricity network, perfect power quality can be hardly achieved.

Different characteristics of power quality are found. These include voltage disturbances, frequency and interruptions. However, voltage disturbances were identified as a concern when wind turbines are grid connected.

Two power quality characteristics that are discussed in this chapter are voltage variations and flicker. This was based on the findings in literature survey.

Voltage variations are as a result of variations in wind speed. Small voltage fluctuations that occur at frequencies below 10Hz are termed flicker. A human eye can see these voltage fluctuations, as it is sensitive at frequencies between 8 and 10Hz. Flicker is measured using a flickermeter. A flickermeter uses voltage to determine flicker. A quantity called  $P_{st}$  is used. However, flicker from wind turbines is not determined from voltage measurements alone, as the background flicker of the grid could influence this method. Some of the methods for determining flicker emission by wind turbines are defined below:

- Active and reactive power measurements and
- Voltage and Current measurements.

Voltage and current measurements were used to calculate flicker at Klipheuwel wind farm.

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## 5. VOLTAGE FLUCTUATIONS AND FLICKER CALCULATIONS

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This chapter presents voltage fluctuations and flicker studies that were carried out to highlight the effects that grid connected wind turbines could have on weak networks. These studies were done by calculation, using DigSilent load flow studies and measurements were taken on Klipheuwel wind farm as will be discussed in chapter 6. The DigSilent studies were done to show the effects of changing power production of an induction generator, as a distributed generator, connected to an 11kV network. An induction generator was chosen as the studied wind turbine use this type of a generator. This chapter seeks to investigate the condition that lead to voltage fluctuations and flicker.

An introduction to DigSilent software is discussed in this chapter followed by different models used to model some electrical components of a grid. Load flow calculations are done on a two-node system to calculate voltage variations due to change in grid strength. Wind speed measurements were done in Klipheuwel and the power output of a wind turbine, in particular, Vestas V47, was calculated and presented in this chapter. Flicker measurements that were done before and after wind turbine installation in Klipheuwel are presented. The last section is a summary of the findings in this chapter.

### ***5.1 Modelling Wind Turbines Using DigSilent***

DigSilent Software has the ability to simulate load flow, RMS fluctuations and transient events. It provides a comprehensive library of models of electrical components. DigSilent was then used for modelling wind turbines and load flow calculations were carried on these models. Dynamic Simulation Language (DSL) of

DigSilent makes it possible for users to create their own block sets or modify the ones in the library [13]. In this chapter, DigSilent models that were used are described as well as how wind turbines are modelled for power quality studies.

### 5.1.1 Induction generator mode!

As wind turbines are equipped with generators, either synchronous or induction generator, it is therefore essential to include the models of these generators in this report. DigSilent provides models for these generators and are integrated in the program. below shows an equivalent diagram of an induction generator as used in DigSilent. This generator was the one chosen when modelling wind turbines in this chapter, as most wind turbines are equipped with this generator.

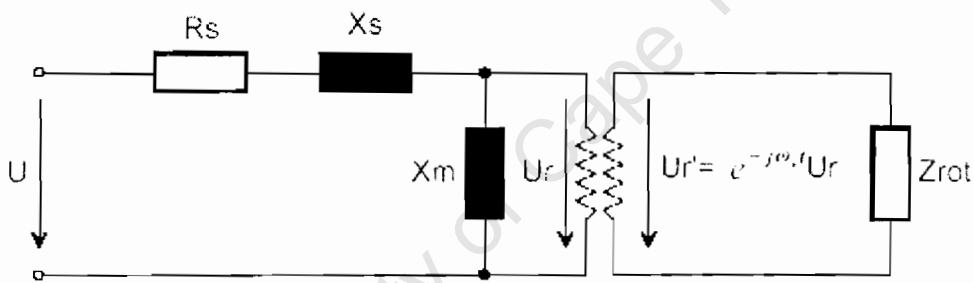


Figure 5. 1 Induction generator model [5]

### 5.1.2 Transformer model

A transformer model is also found in the DigSilent library and is shown in figure 5.2. This transformer is used to step up the 690V generated by the wind turbine to the 11kV of the grid.

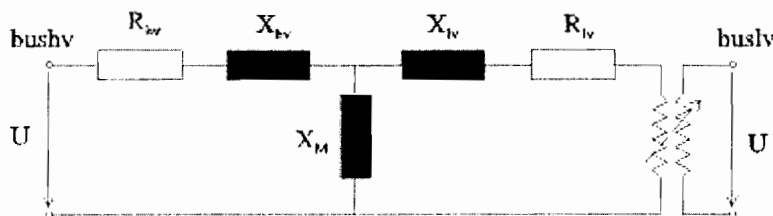


Figure 5. 2 Transformer model [5]

### 5.1.3 Line Model

The following model is that of a line as used on DigSilent. This model was used for the connection between the wind farm and Klipheuwel. The characteristics of this model were modified to suit that of an 11kV cable.

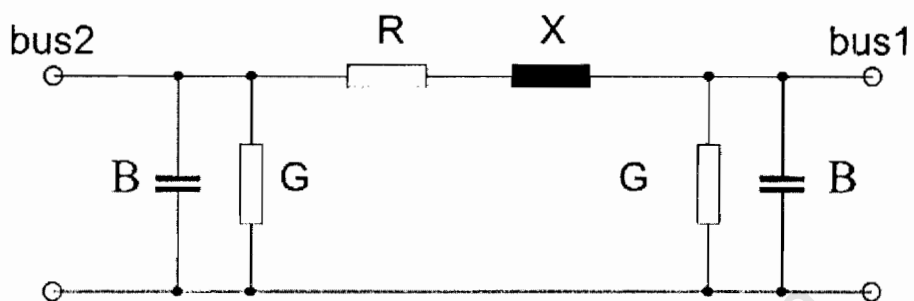


Figure 5. 3 Line Model [5]

### 5.1.5 Wind Turbine Model

An overall structure of a wind turbine model is composed of an electric model, mechanical model, aerodynamic model and the wind model. The connection on these models is as shown in Figure 5. 4. The electrical model is composed of built-in models, like the grid, transformers, capacitors and generators. While aerodynamic and mechanical model, and wind speed are modelled using DSL. However, wind speed was not modelled during these studies as it requires an external program, hence more accurate results were obtained by measurements as discussed in chapter 6.

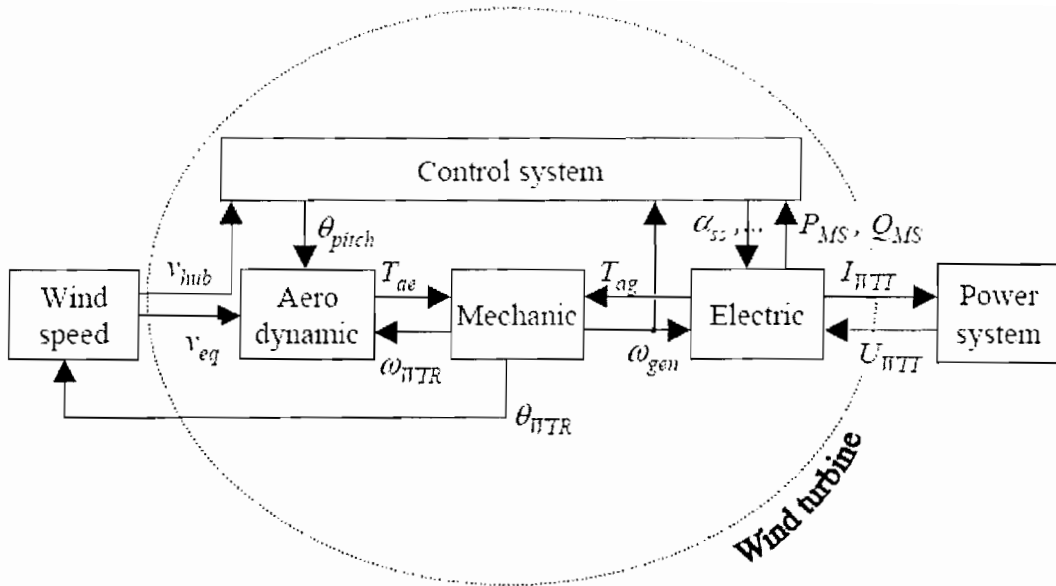


Figure 5. 4 Wind Turbine Model [5]

## 5.2 Load Flow Calculations

### 5.2.1 Steady state operation:

#### Case Study 1: Two-Node impedance model

A simple impedance model was modelled using DigSilent Software, and load flow calculations were carried out. These calculations were done to study how the voltage will change depending on the power output from a generator, either synchronous or induction generator. In this case, an induction generator was chosen, as it is the most common used in wind turbines. A line impedance grid was varied from an X/R ratio of 0.5, 0.75, 1, to 2. Voltage at the Point of Common Connection (PCC) was studied and the results obtained were plotted as shown in Figure 5. 5. Simulation results and

electrical data for the generator are given in Appendix B.

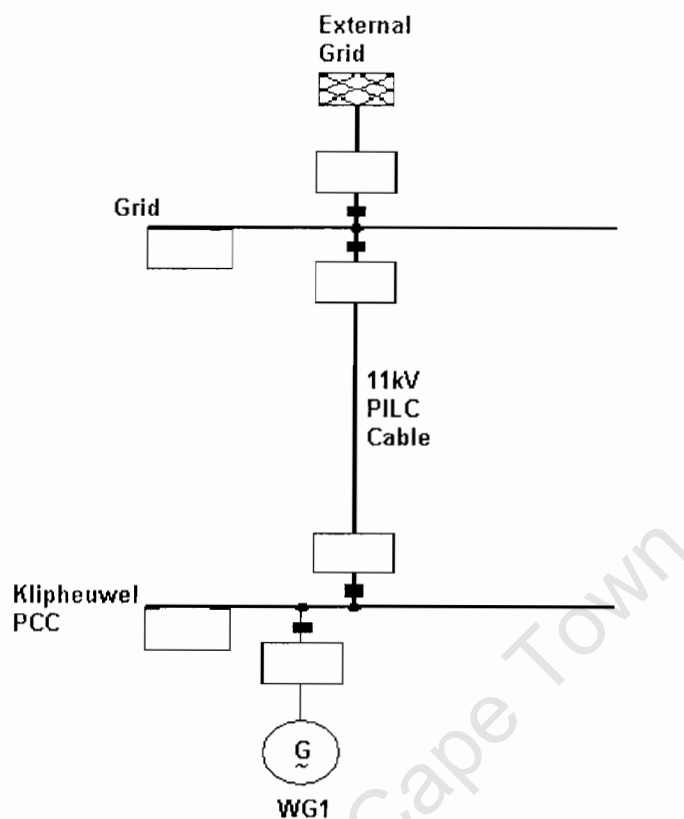


Figure 5. 5 Simple Impedance Model used to calculate voltage fluctuation

From the graphs, it has been seen that at low X/R ratios, i.e. X/R ratio  $\leq 1$ , the voltage variations are high and the voltage at PCC increases with an increase to active power generated by the induction generator. However, this voltage increase is low at high X/R ratios of about 2. This is because the active power produced by the generator causes a voltage increase due to the grid resistance. The reactive power consumed by the generator causes voltage drop over the grid reactance. For an X/R ratio of about 2, these voltages approximately have the same size.

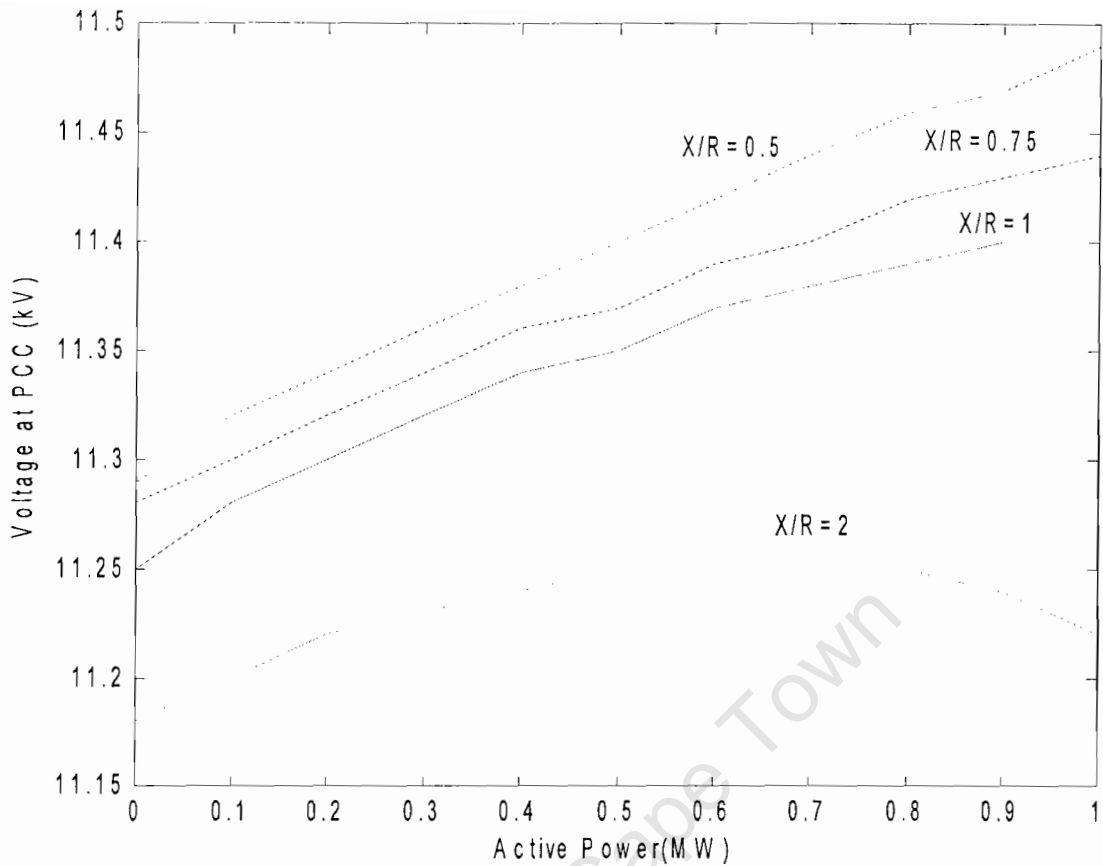


Figure 5. 6 The effects of X/R ratio on voltage variations

## Voltage Variation Calculations

According to Larsson, [21], two different phenomena occur between the grid and the turbine. These are the stationary variation in the power production and power fluctuations. Both of these phenomena have an impact on voltage variations. Stationary voltage variations are the results of the power produced by the turbine, while power fluctuations that occur at a frequency of 1 to 2 Hz are mainly caused by the tower shadow [21].

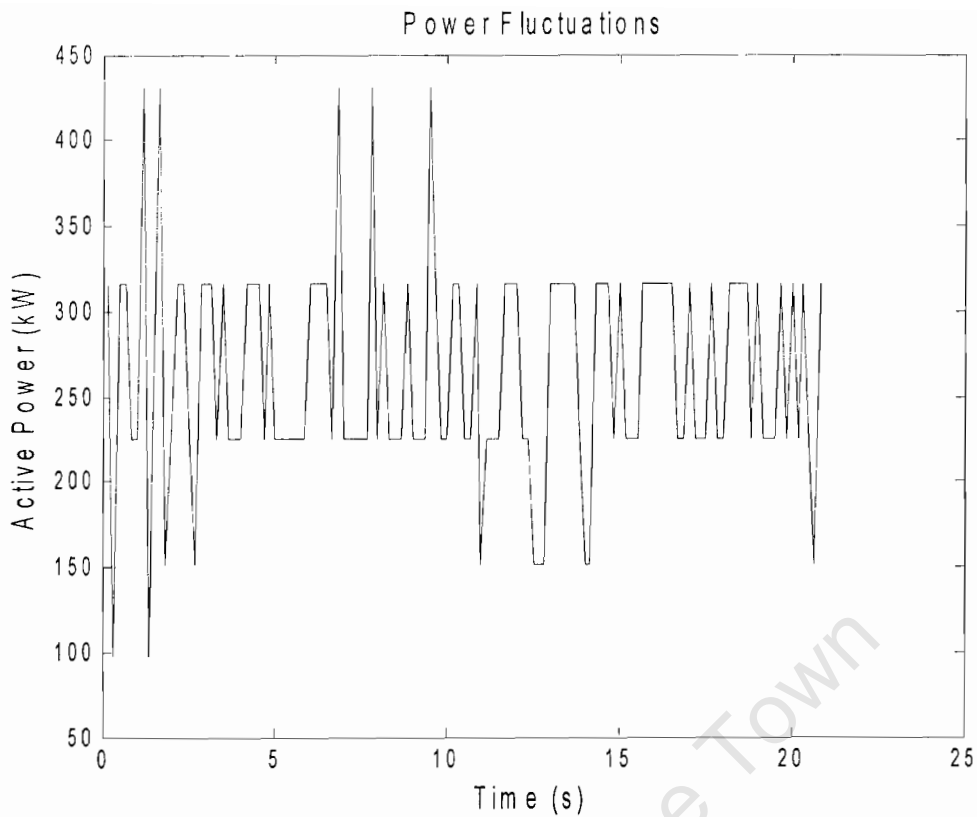
### 5.2.3 Power Fluctuations due to wind variations

Power from the wind turbines is determined by the equation

$$P = \frac{1}{2} C_p \rho V^3 A \dots\dots\dots(5.1)$$

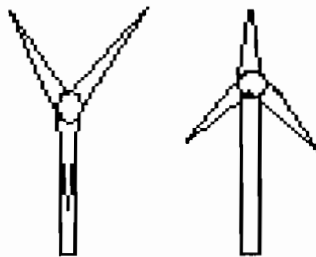
From this equation, it is clear that wind variation will affect power output as it is related to wind speed by the power of 3. Also, tower shadows results in power fluctuations when the position of the blade passes the tower, the power will drop. For a three bladed tower, the power drop will appear 3 times. This is known as a 3p frequency. The frequency of power fluctuation is equal to the number of blades multiplied by the rotational speed. The graph below shows both the wind variation effects and tower shadow. The peaks show tower shadow effect while the fluctuations show the wind variations. The power shown below was calculated using equation 5.1 above, with the measured wind speed from the wind farm. Wind turbine V47 from Klipheuwel wind farm was used as an example in this calculation, with  $A=1.735 \text{ m}^2$ ,  $C_p = 0.593$ , and  $\rho=1.225 \text{ kg/m}^3$ . The average power calculated is about 266kW, which corresponds to an average wind speed of about 7.09 m/s. Wind speed variations were used to calculate the output power. The spikes in the figure show tower shadow effects at a frequency of about 1.7 Hz. This implies that the turbine was rotating at 34 rpm, which is slightly higher than the given limits for the V47 rotation speed in table 3.1.

University of Pretoria



**Figure 5. 7 Calculated power fluctuations**

The effect of tower shadow and wind gradient to power fluctuations can also be seen when one blade passes the tower, none of the blades is at the highest point, and hence, power output is at its minimum level. Whereas, if one blade is at its highest point, none of the other two blades is at the lowest point or behind the tower, hence power will be at its maximum point. This cycle is repeated 3 times per revolution, for a three bladed wind turbine. This illustration is as shown in.



**Figure 5. 8 Tower Shadow Effect**

High power fluctuations occur at high wind speed, as wind speed fluctuation increase with wind speed [21].

### 5.2.4 Active and Reactive Power Consumption

An increase in active power produced, results to an increase in reactive power consumed. This was the case in the case study as shown in Figure 5.9 below.

### 5.3 Flicker during Continuous Operation

Flicker is a measure of dynamic voltage fluctuations. It is based on the fact that people are irritated by the flickering of the light bulb. The level of flicker is classified by a dimensionless quantity,  $P_{st}$ , measured over a 10-minute period.  $P_{st}$  is most sensitive to voltage fluctuations on frequencies around 8.8 Hz. According to IEC 61400-21, flicker is determined by measurements of current and voltage. The short-term flicker is calculated using a reference grid.

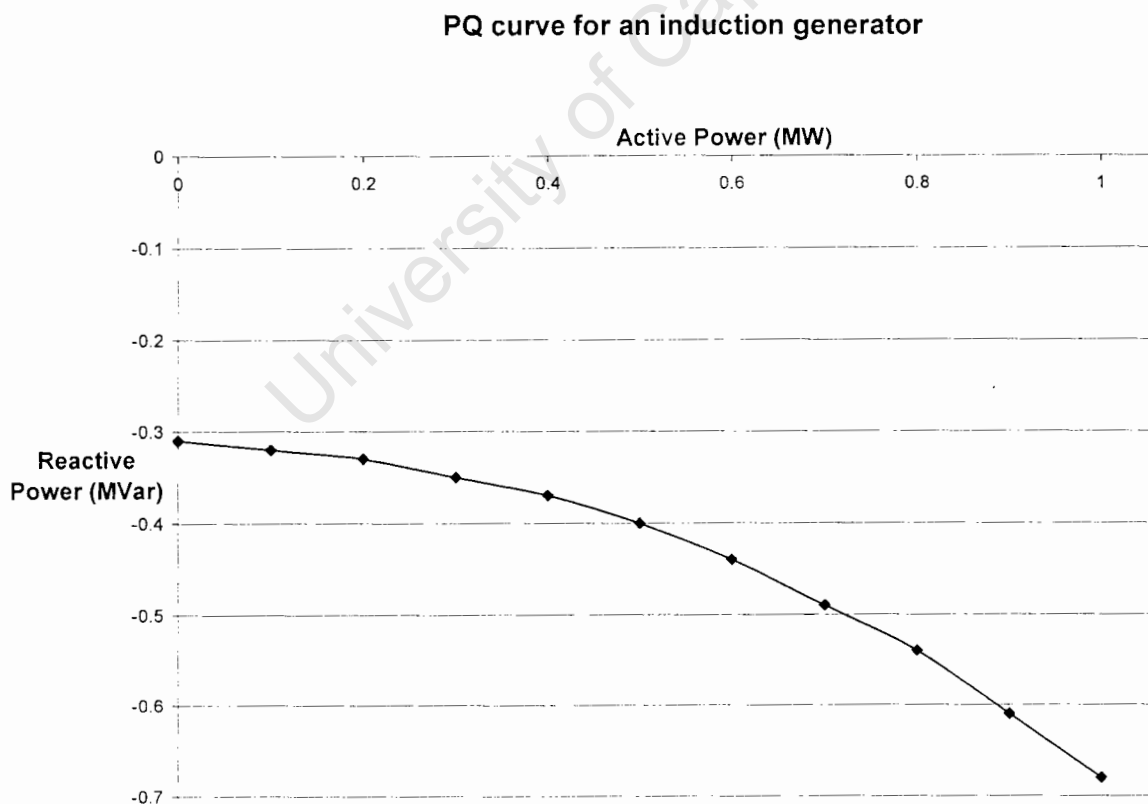


Figure 5.9 Active/Reactive Power Curve for an induction generator

### 5.3.1 Combined flicker emission

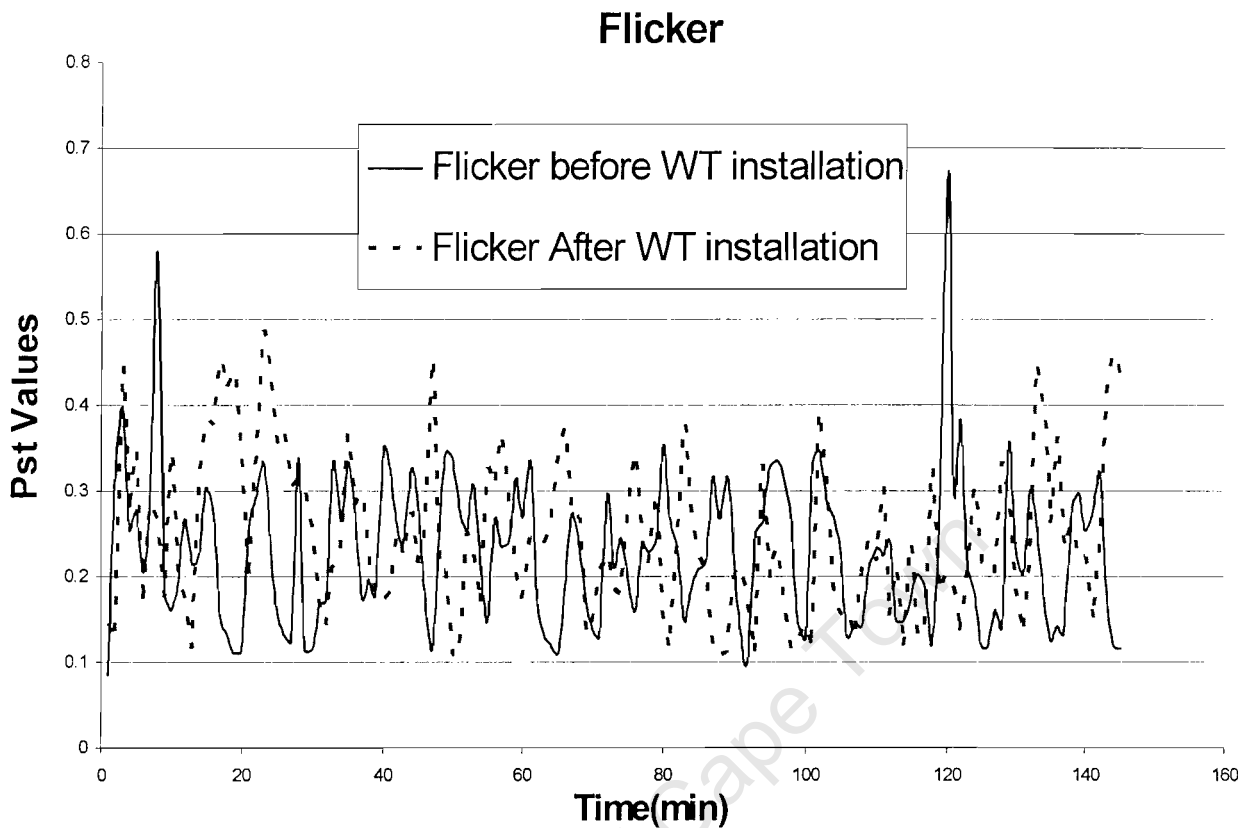


Figure 5. 10 Measured flicker before and after wind turbines installation

Flicker was monitored in Klipheuwel substation before and after the installation of the wind turbines. According to the results obtained, wind turbines did not have a huge impact on voltage flicker as the measured flicker before the wind turbines installation is approximately the same as the one after the installation. The graph shows only one day data, which is representative of a week data. The rest of the data is not shown as it is repetitive.

The measurements were however, done under different conditions, compared to the measurements explained in chapter 6. Firstly, the measurements were taken at the point of common connection (PCC), which is where the other loads such as farmers are connected. The PCC is about 5 km away from the source, and hence the lower flicker values. The low flicker values at the PCC could mean that the grid is not experiencing high voltage fluctuations especially at frequencies between 1 -10Hz.

Hence, the high flicker emission is seen when measured closer to the source, as will be discussed in chapter 6.

## 5.4 Summary

In this chapter, a study was conducted on DigSilent software to measure power quality of a wind turbine. A case study was done, where a wind turbine is represented by an induction generator to simulate steady state voltage variations. This type of a generator was chosen because the wind turbine V47 uses an induction generator. A two-node model was used to simulate a distribution network with a distributed generator. The results obtained from load flow analysis of this case study show that at low X/R ratios of the grid, i.e. X/R ratio  $\leq 1$ , the voltage variations are high and the voltage at PCC increases with an increase to active power generated by the induction generator. However, this voltage increase is low at high X/R ratios of about 2. This means that for electrically weak networks, voltage variations are expected to be high when a distributed generator is connected to them.

Expected power fluctuations from a wind turbine were calculated using measured wind speeds from Klipheuwel wind farm. The equation  $P = \frac{1}{2} C_p \rho V^3 A$  was used for this calculation with A as a swept area of V47 wind turbine. Power fluctuations are as a result of tower shadow effects as well as wind speed variations.

Flicker was monitored in Klipheuwel substation before and after the installation of the wind turbines. According to the results obtained, wind turbines did not have a huge impact on voltage flicker as the measured flicker before the wind turbine installation is approximately the same as the one after the installation. Because these measurements were done at the substation, where other loads could have an impact on results obtained, more accurate results are to be obtained by measurements at the generator terminals of each wind turbine. The following chapter represents power quality measurements taken from one of the three Klipheuwel wind turbines.

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## 6. POWER QUALITY STUDIES ON KLIPHEUWEL WIND FARM

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This chapter present the results obtained from Klipheuwel wind farm, the power quality studies that were carried out as well as methods used to do measurements.

Different options on taking measurements were considered. These included taking measurements from Klipheuwel substation, where the wind farm is connected. However, this option meant that the studies would be of the wind farm and not the individual wind turbines. It would then be difficult to conclude on whether variable speed wind turbines have different power quality impacts compared to fixed speed wind turbines. Also, this option would not reflect the pure flicker and voltage variation as a result of wind turbines, as there are other loads connected to the substations.

The next option was to measure power quality from each wind turbine. This was the preferred option as it would lead to constructive conclusions about types of wind turbines, and the actual impact that each could have. This option came with its constraints as well, such as not being able to take measurements from the other two wind turbines. Also, taking measurements from each wind turbine would require three times the number of equipment required for data capturing. The measurements would have to be taken at the same time for comparison purposes. However, this would be the more accurate option.

During the measurement period, only one wind turbine was studied, Vestas V47. Jeumont J48 had a hydraulic malfunctioning. Vestas V66 has its 690V/11kV transformer in the nacelle. This meant that for generator terminal measurements, the data logger would have to be connected in the nacelle, which is on top of a 60m tall tower. This would then mean that to collect data, I would have to climb up weekly,

as the data was collected weekly, with a supervisor from Eskom. This scenario was discussed with an Eskom employee and the decision not to take the measured from V66 was then reached, based on the constraint of climbing 60m weekly. However, this also meant that conclusions on the effects of different types of wind turbines could not be made. The option of taking measurements from only on wind turbine was then reached.

The next challenge was to choose a suitable data logger. Firstly, a flickermeter was considered. Flickermeter uses voltage to determine flicker, which is not enough for modelling flicker emission by wind turbines. Also, flickermeter would give a value for flicker, with no indication of power fluctuations, which gives an indication of wind speed fluctuations.

A data logger, which could measure both current and voltage, and calculates  $P_{st}$  value according to IEC 868, measure active and reactive power output, was required. The logger would have to have enough memory, at least 1MB to store data for seven days, 24hrs a day and at a sampling frequency of at least 1kHz. 3 sets of current clamps were required for current measurements, as well as voltage test leads. Current clamps had to be of diameter equal or greater than the diameter of the conductor, which is about 40mm for V47. These current clamps would have to be able to withstand a current of about 600A and above. The logger would need to be able to communicate with an external computer for data transfer. Different power quality analysers were checked and CA 8334 Power Quality analyser was chosen. This data logger is described in the next section.

### **6.1.1 Equipment Description:**

CA 8334 Power Quality Analyzer by Chauvin Arnoux was used for the power quality measurements from the wind turbines. This power quality analyzer is used together with 3 times Ampflex for current measurements and voltage test leads. The diameter of the Ampflex is 250mm with a measurement range of 10A to 6500A (rms). CA 8334 was calibrated in Eskom's metrology lab in Brackenfell, Cape Town. It was then installed on V47 terminals for data capturing. Data was

downloaded weekly to a laptop using RS 232. Qualistar View 2.3 was used to read the data and Matlab and Excel were used for data analysis.

### 6.1.2 Electrical Specifications for CA 8334

The sampling frequency for the CA 8334 is 12.8 kHz per channel at 50 Hz, which means 256 samples per period. The operating voltage input is 960 Vrms phase to phase, and 480 Vrms phase to neutral. 1.2 Vn (nominal voltage) is an acceptable voltage overload while 2 Vn is only admissible for 1 second.

### 6.1.3 Schematic of proposed measurements:

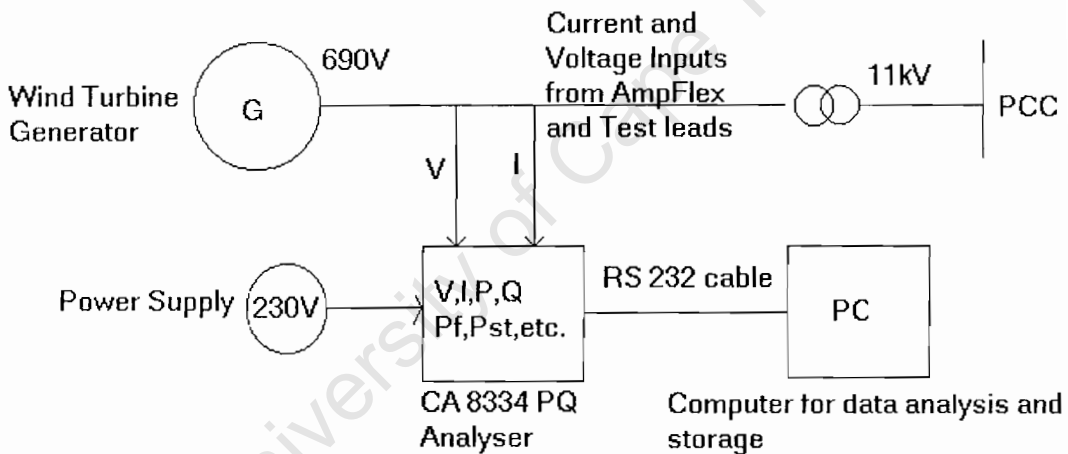


Figure 6. 1 Data Capturing Set-Up

The connection of CA 8334 was as shown in Figure 6. 1. The power quality analyser was connected as shown and left to download data for a month. However, data was downloaded to a laptop weekly for analysis. Figure 6.3 is that of V47 wind turbine, with the 690V/11kV transformer situated outside the tower. This made it easier for the data recording from this wind turbine.

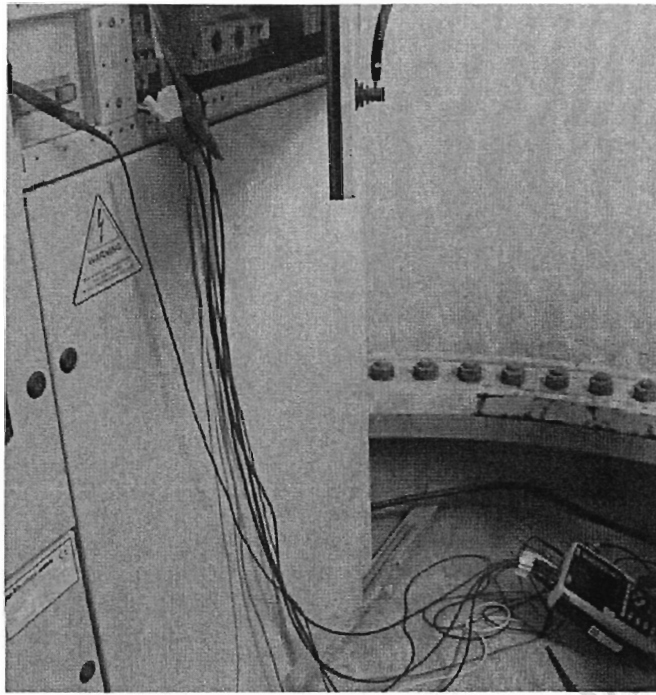


Figure 6. 2 The connection of CA 8334 to V47 wind turbine



Figure 6. 3 V47 Wind turbine with V66 as the furthest turbine

## 6.2 Results Analysis

In this section, the measured power quality characteristics from Vestas V47 wind turbine in Klipheuwel wind farm are discussed. The data collected was similar for all four weeks of data collection; hence, only one-week data is presented and interpreted. However, the rest of the measurements are presented in Appendix A.

### 6.2.1 Wind variations

Using the formula  $P = 0.5 * C_p * \rho * V^3 * A$ , wind speed from Klipheuwel was calculated to have varied from below 4m/s to be about 7.975m/s. Power generated by the wind turbine was used to calculate the input wind speed. The formula stated above was used to determine the wind speed that could have resulted to such power output. The wind speed fluctuations are presented in. The wind speed tends to be high in the afternoon, between 3pm and 6pm. This was the case for all four weeks of data capturing. However, the measured wind speed from Klipheuwel showed a varying averaged wind speed from about 1m/s to approximately 11m/s. the wind speed was measured by Eskom, using an anemometer. This data is also shown in Figure 6. 5. The two graphs show similar fluctuations except for the actual values, especially for the wind speed values below 4m/s. This is because the measured power from the turbine was either negative or positive depending on whether the turbine was generating power or consuming it from the grid. This is explained from the power curve where at low wind speeds below 4m/s, the wind turbine produces no power; hence the turbine acts as a load. As a result, the calculated wind speed at negative power output was negative. Those values were hence replaced by zero when calculating the average wind speed. The wind speed was calculated over one-minute and averaged over an hour to correlate with the logged wind speed data from Klipheuwel. The same period was used for analysis.

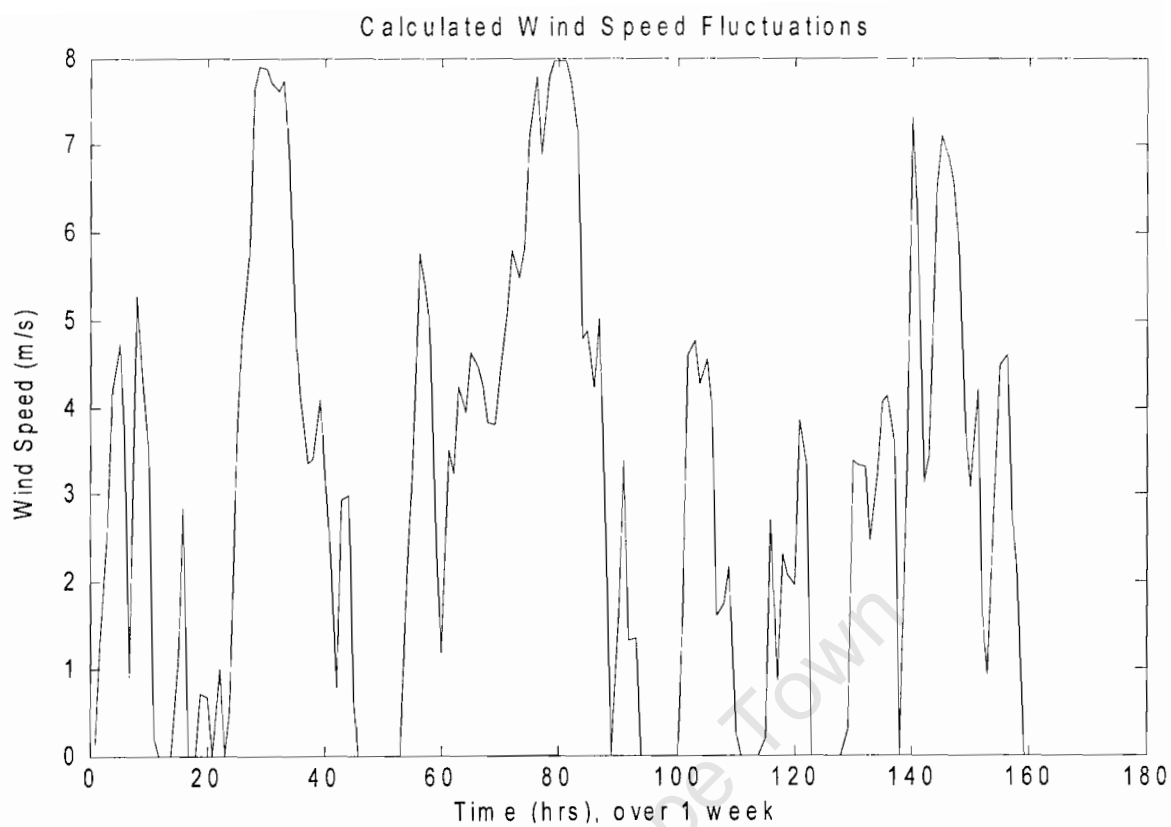


Figure 6. 4 Calculated Wind Speed

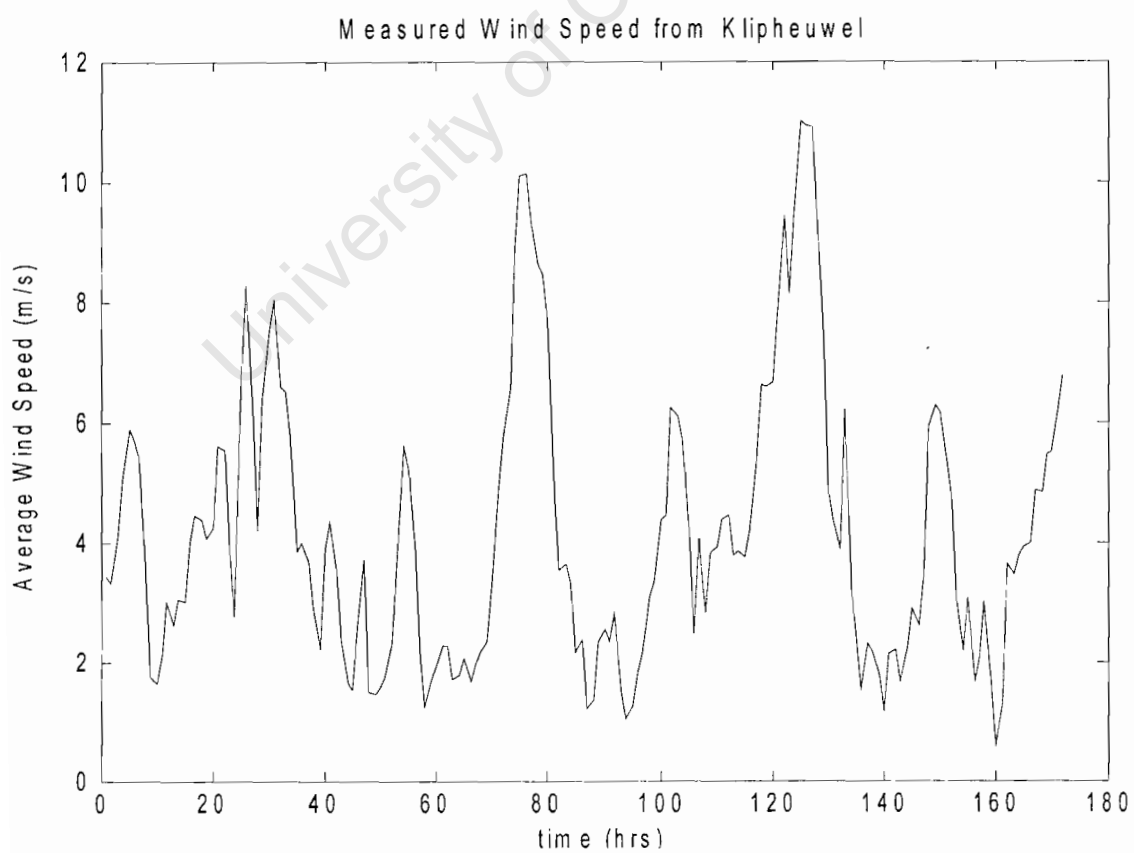


Figure 6. 5 Measured Wind Speed from Klipheuwel

## 6.2.2 Voltage Variations

The measured voltage from the wind turbine fluctuates between 692V and 727V. The rated voltage for this wind turbine is 690V +10% / -6% as stated by the manufacturer. The fluctuations are still within the limits but indicate the variation of wind speed. Voltage variations were expected at the terminals of a wind turbine due to wind variations. The following voltage measured at the wind turbines' terminals shows the voltage fluctuations. Voltage fluctuations are high at high wind speeds. The measurements are done on 1-minute integration period.

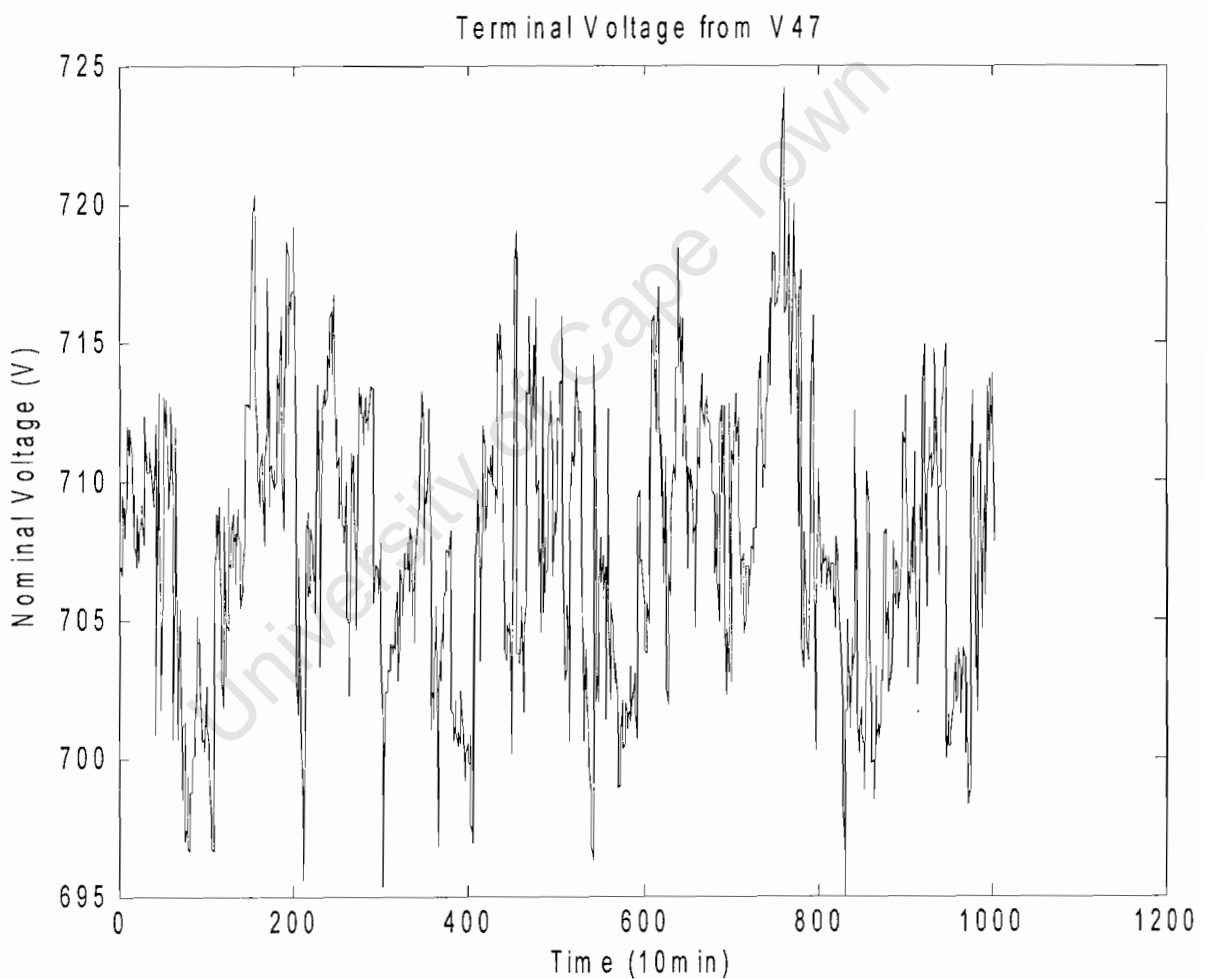


Figure 6. 6 Nominal voltage from V47

## 6.2.3 Power Fluctuations

Power fluctuations are said to be as a result of voltage fluctuations, which are due to wind speed fluctuations. The measured power output is as shown in Figure 6. 7 and compared with calculated output power. The fluctuations appear slightly similar, but calculated values are higher than measured values. Power fluctuations occurring at a frequency of 1 to 2 Hz are mainly caused by the tower shadow effect.

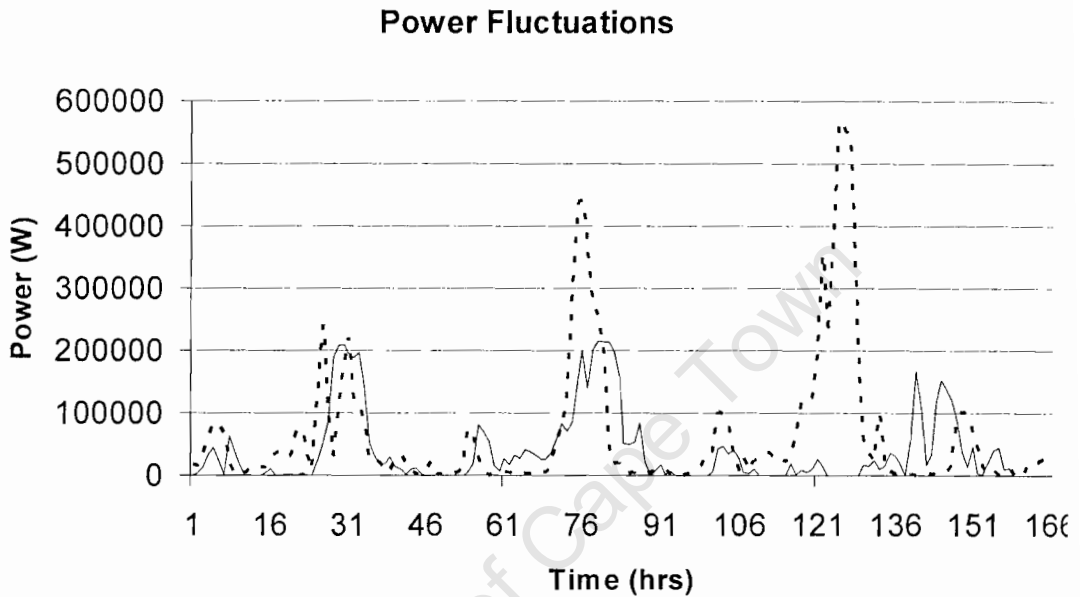


Figure 6. 7 Comparison of measured power (solid) and power calculated from wind speed (dotted)

#### 6.2.4 Active and Reactive Power Consumption

The measured power output showed an import of reactive power while exporting active power. This implied that the wind turbine uses induction generator as it showed the same pattern throughout the data collection period. The measured reactive power is not in proportion with the measured active power compared to Figure 5.9.

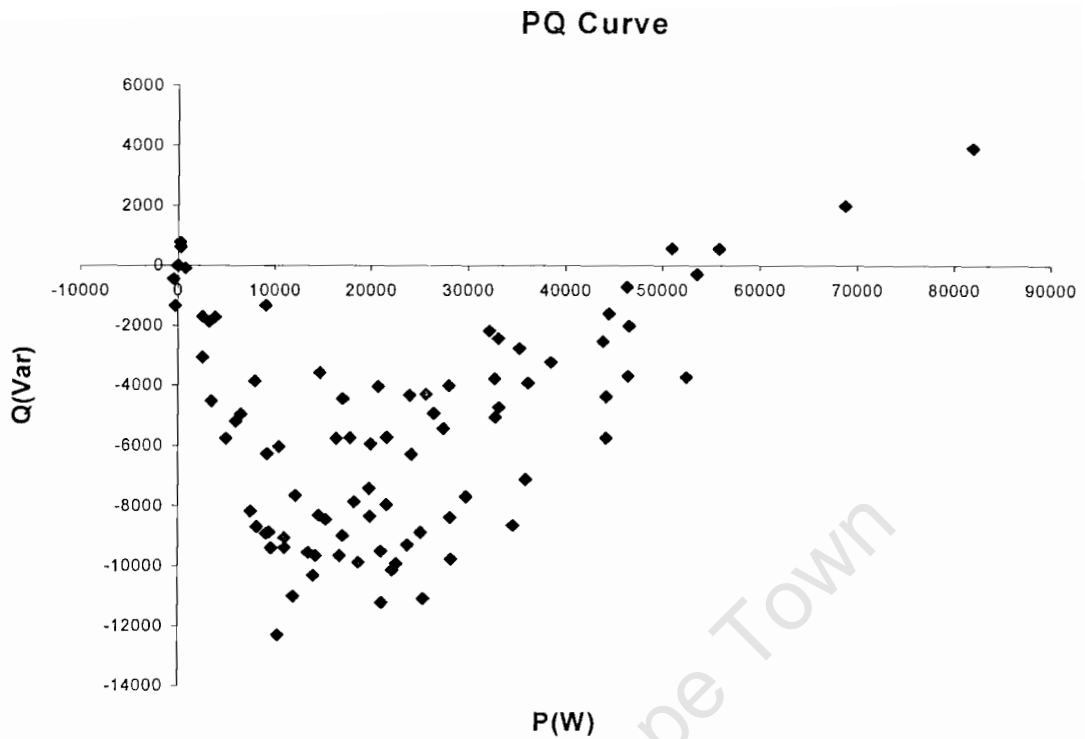


Figure 6. 8 The relationship between active power export and reactive power import

### 6.2.4 Frequency

The grid frequency is  $50\text{Hz} \pm 1\%$ , however, the measured frequency from the wind turbine terminals was kept within the limits. This indicates that these grid connected wind turbines do not affect the frequency of the grid, as indicated in the literature. However, autonomous wind turbines are expected to result in high frequency fluctuations. The spinning reserve is small in an autonomous grid supplied by diesel engines. The small spinning reserves will give rise to frequency fluctuations in case of a sudden wind rise or wind drop. The measured frequency is as shown in Figure 6. 9.

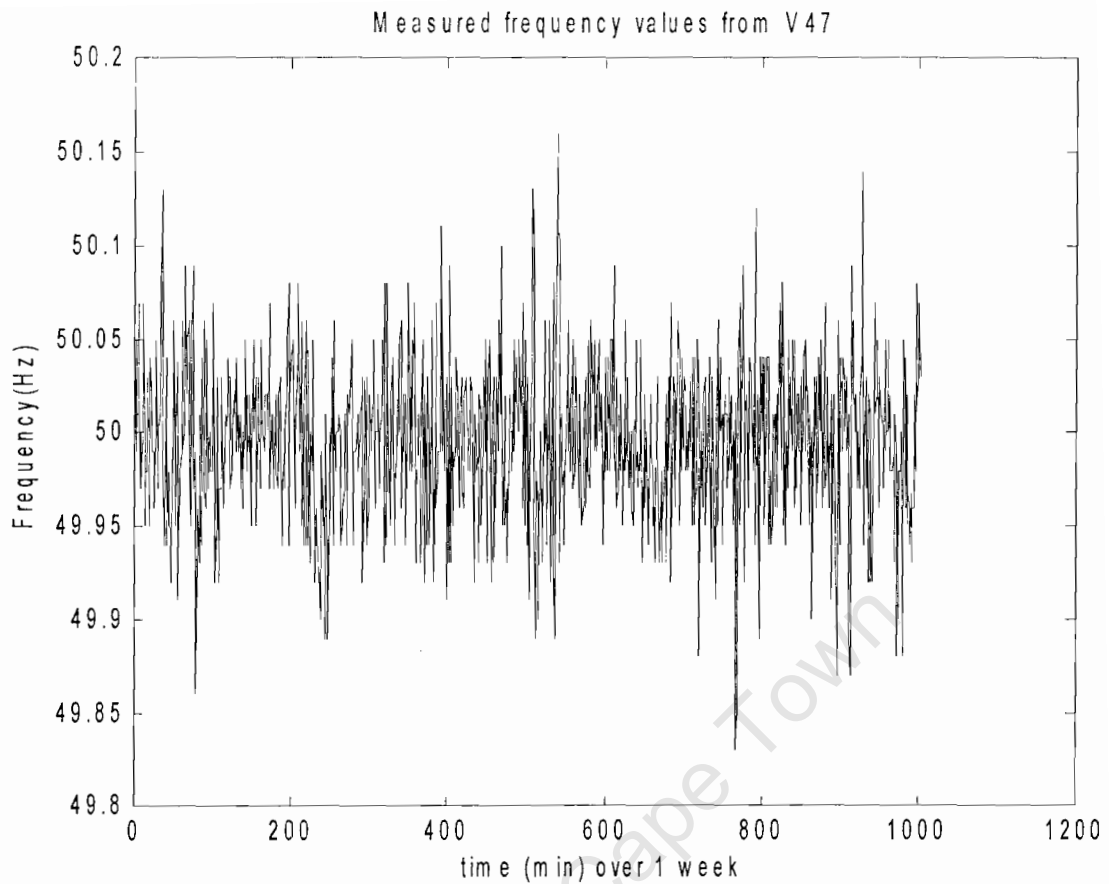
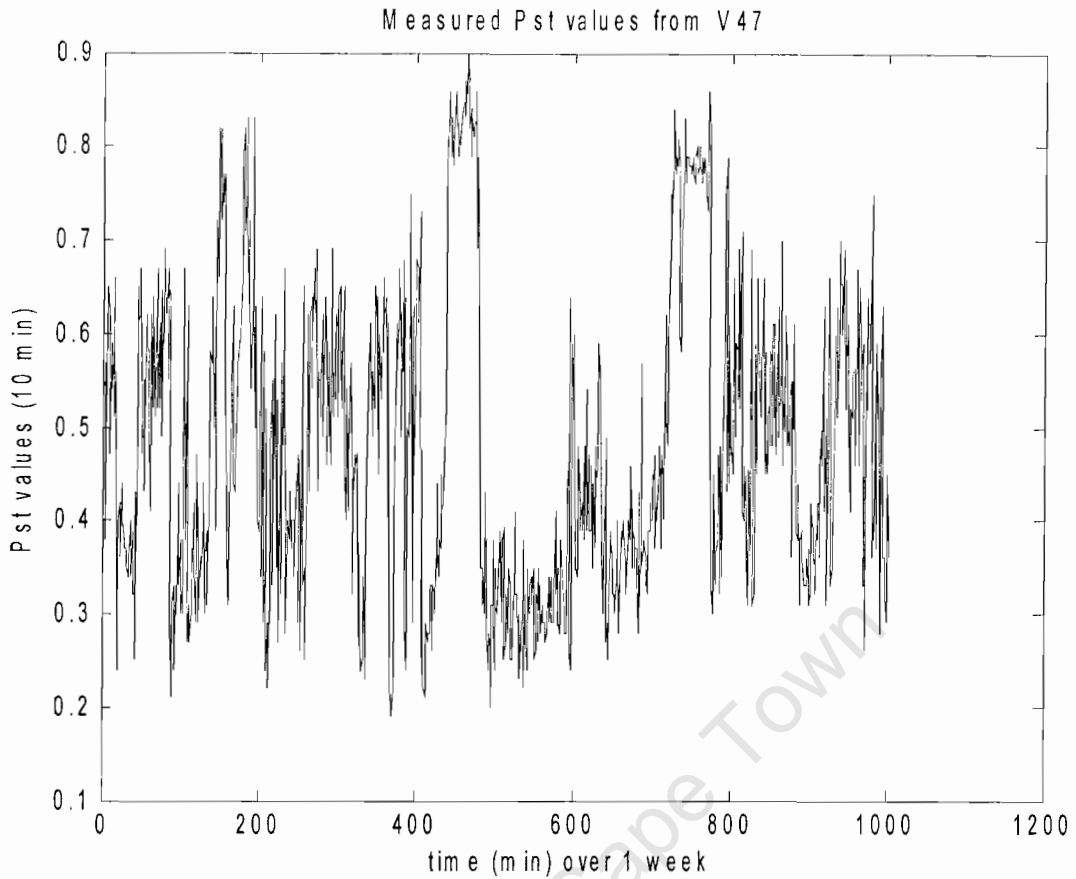


Figure 6.9 Wind Turbine V47 Frequency

### 6.2.5 Flicker during continuous operations

The measured  $P_{st}$  values are as shown in Figure 6.10. This shows relatively high flicker values for a variable speed wind turbine. The highest recorded  $P_{st}$  value is about 0.91. High flicker values are obtained at high wind speeds and are the results of high voltage fluctuations. Methods used to calculate  $P_{st}$  values in CA 8334 are adopted from IEC 61000-4-15.



**Figure 6. 10 Flicker emitted by V47 (28/10 -04/11)**

$P_{st}$  values were measured and are shown in Figure 6. 11 in relation to the output power. High  $P_{st}$  values were recorded at low power output, but generally the flicker emission increases with active power output. The measured flicker shows a maximum  $P_{st}$  value of about 0.91, corresponding to a power output of about 200 kW, which is substantially below the rated power of 660 kW for the generator. This is a very high flicker value as the compatibility level identified in the national standard [30] is 1. Also, flicker approached the specified limit at speeds as low as 1/3 of rating. The high flicker values show that the closer to the source, the higher the flicker emission level.

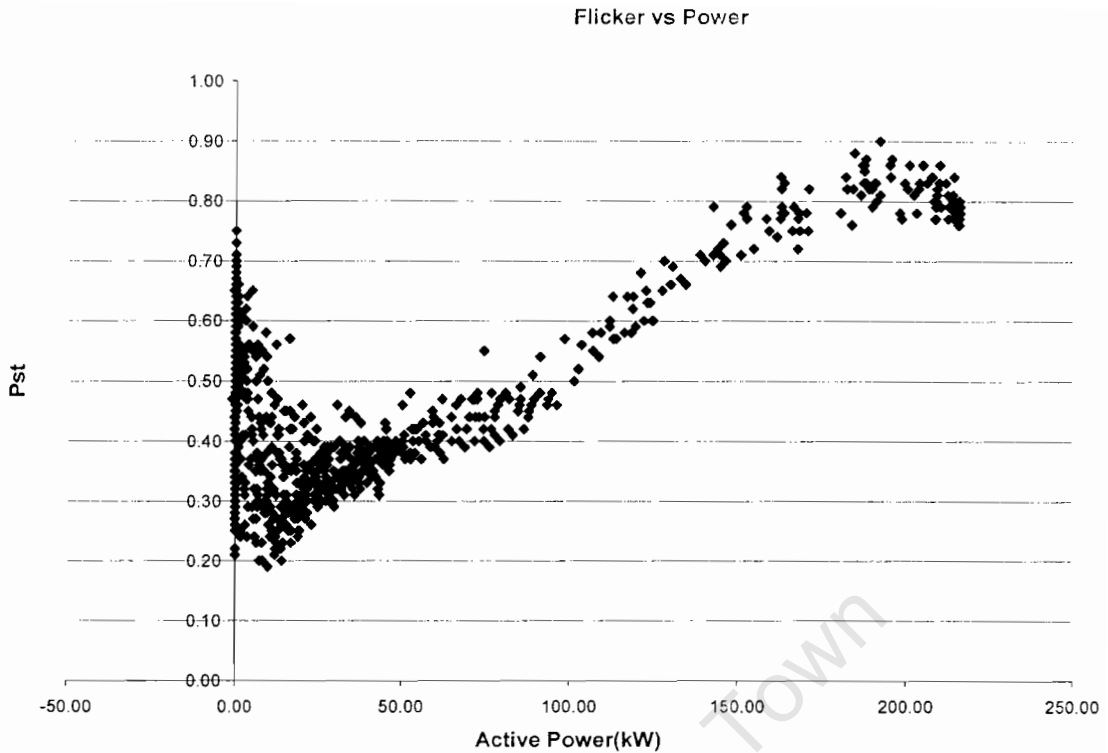


Figure 6. 11 An increase in flicker emission at high power output

### 6.3 Summary

This chapter explained the background to flicker studies done in this thesis. The measurements were taken on one of the three wind turbines in Klipheuwel, which is the Vestas V47 wind turbine. The reason behind this decision was that the Jeumont was malfunctioning during the measurement period, while the problem with V66 was that measurements would have to be taken from the nacelle itself as the 690V/11kV transformer is situated there. This would be a constraint as it meant climbing 60m weekly to capture data.

Different measuring methods were studied, as well as different measuring devices. A data logger with active and reactive power measurement capabilities, voltage and current, as well as flicker was chosen as being CA 8334 Power Quality Analyser. Measurements were taken for a month and downloaded weekly for analysis.

Voltage variations were recorded and reported to be in proportion with variation in wind speed. Power fluctuations were also reported and found to be as a result of fluctuating wind speeds, as well as tower shadow effects at frequencies between 1 and 2 Hz. Results show that wind turbines do not affect the frequency of the grid. V47 wind turbine shows an import in reactive power while exporting reactive power. Another finding was that, as opposed to the literature survey, this wind turbine, which is a variable speed type, emits high flicker. This flicker increases with an increase in power produced.

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## 7. CONCLUSIONS

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Based on the measured data from Klipheuwel and the literature on wind turbines and their power quality, the following conclusions are drawn:

### **7.1 Power Quality**

- The variation of wind speed results to fluctuating power output from the wind turbines. This has been seen both in literature review and during measurements in Klipheuwel. The relationship between wind speed and power is a cube root, meaning that small variations in wind speed will result to higher power variations, which will be cubed that of the wind speed.
- The voltage measured at the terminals of a wind turbine varies according to the variations in wind speed. These voltage variations are seen to be higher at high wind speed. The fluctuating voltages at the terminal of the wind turbines result in fluctuating voltages at the point of common connection.
- Flicker measured during continuous operations was higher at the terminals of the wind turbine. The cause of this high flicker index is associated with the fluctuating power output from the wind turbine as it is higher at high power values. However, the measured flicker at Klipheuwel substation, which is a sum of flicker emitted by all three wind turbines, showed a very little emission by wind turbines as it was compared to flicker before the installation of the wind turbines. The measured flicker from the terminals of the wind turbines is expected to be higher than at point of common connection (PCC) as the fluctuations are higher at the terminals.
- Wind turbines are no threat to grid frequency as seen in both literature review and measured frequency from Klipheuwel. However, this could only be said for grid connected wind turbines.

## ***7.2 Wind Turbine Type***

The type of wind turbines connected to the grid also determines whether the wind farm will have higher impact on power quality. For instance, literature reveals that variable speed wind turbines emit less flicker to the network compared to fixed speed wind turbines. However, the measured flicker from Vestas V47 wind turbine was high, and this wind turbine is of a variable speed type.

Regardless of wind turbine type and regulation method used, the power output fluctuates due to wind speed variations, and the tower shadow. Induction generators, which most wind turbines are equipped with, import reactive power from the grid, while exporting active power. This was shown to be true according to the measured active power and reactive from V47, which is of an induction generator type. However, measurements from other wind turbines would need to be conducted to justify this conclusion.

## ***7.3 Scope for Future Work***

The impacts that wind turbines could have on power quality of distribution network have been highlighted. Literature on how to measure power quality of wind turbines has been collected and explained in this thesis. However, measurements could not be taken from all three wind turbines. Since these three wind turbines are uniquely designed, it would be advisable to take measurements from all three wind turbines simultaneously and monitor the impacts that each have on power quality. This could be very useful if the wind farm is to be expanded, as it would help to make a good decision as to which wind turbine will be more reliable and does not degrade the quality of supply.

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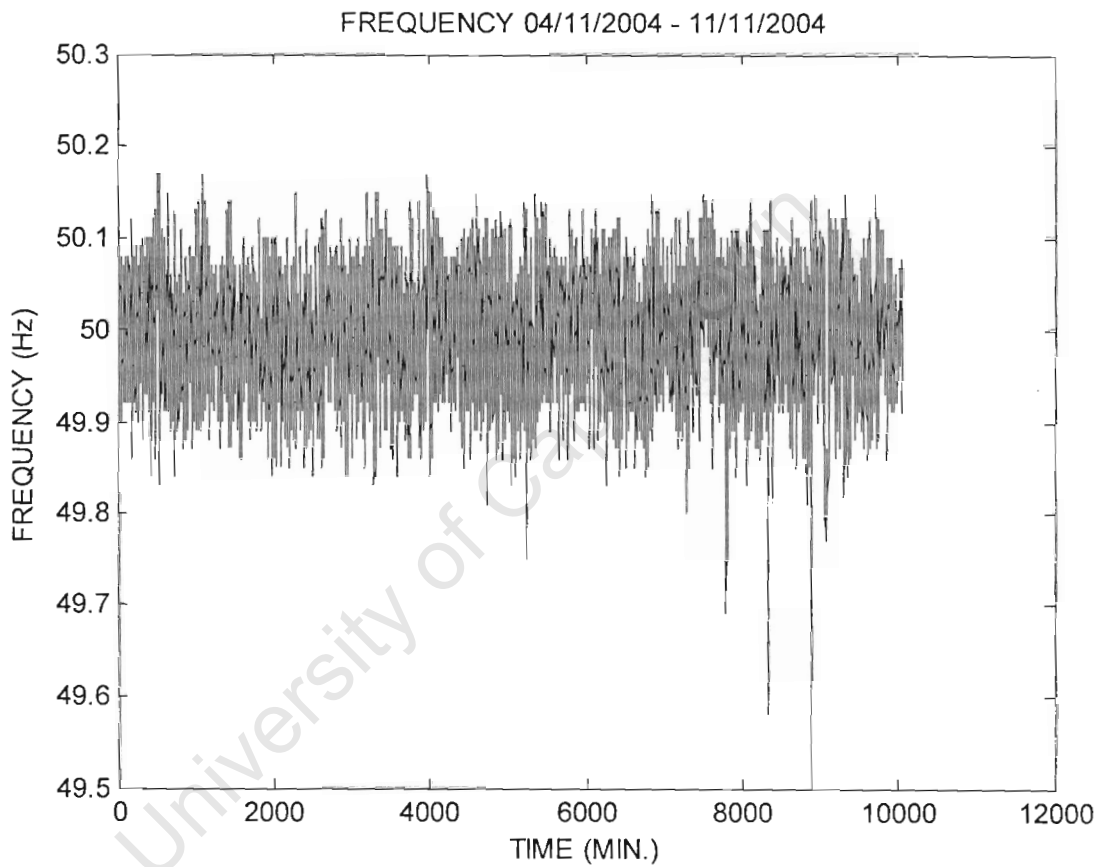
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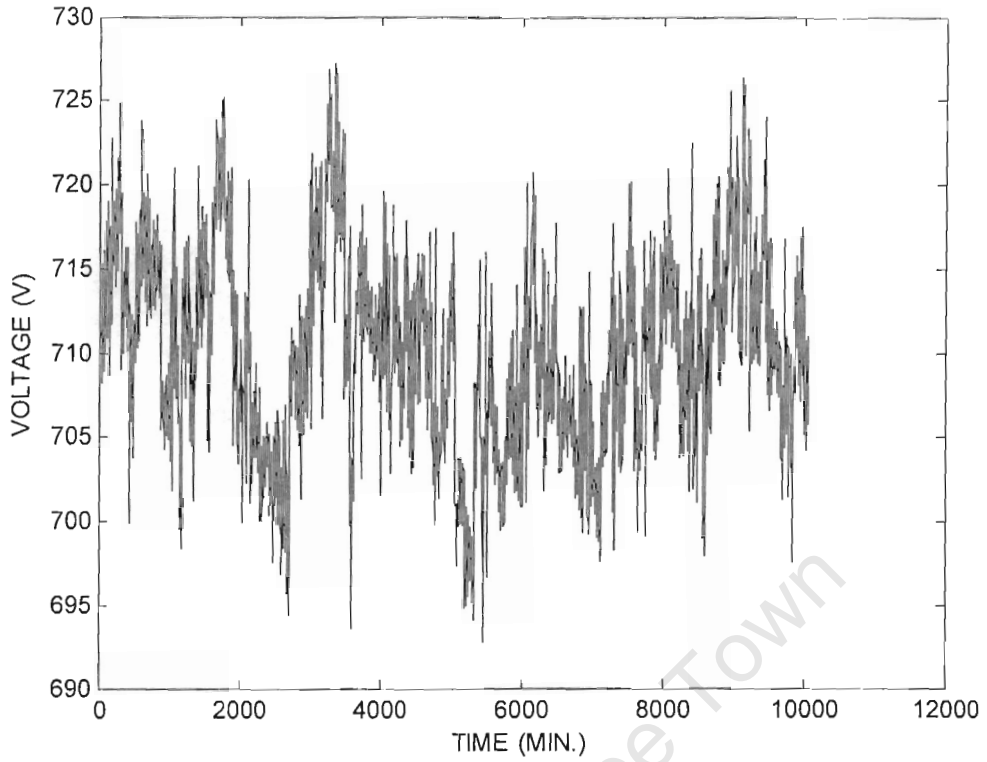
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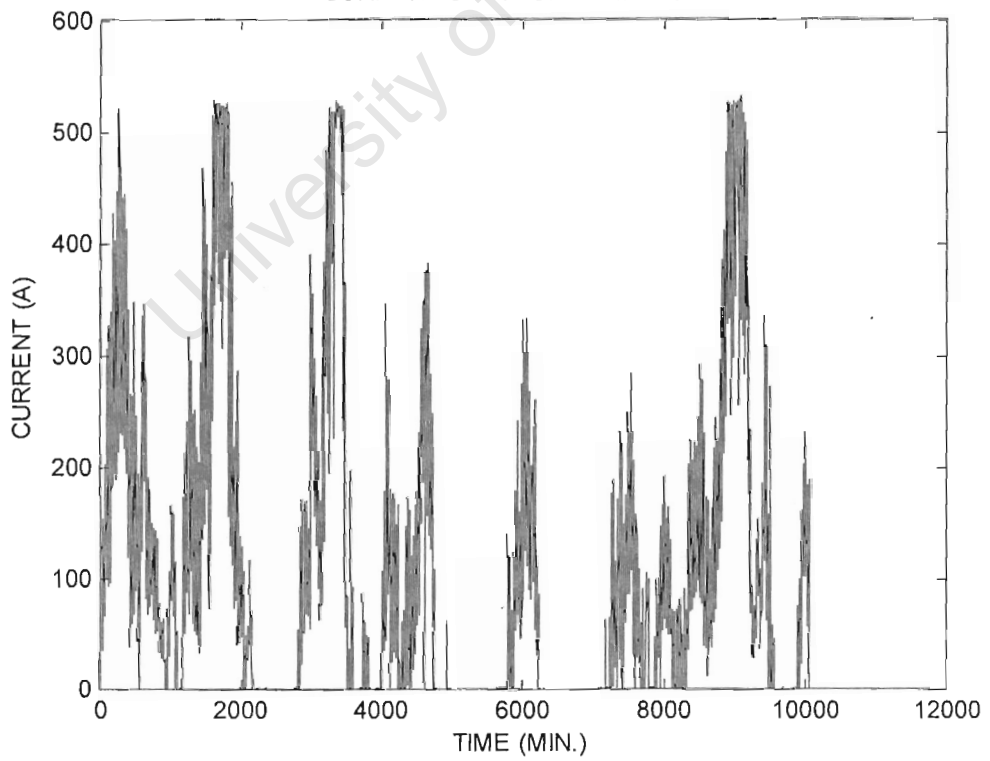
**APPENDIX A: MEASUREMENTS RESULTS**  
**WEEK 2 DATA**



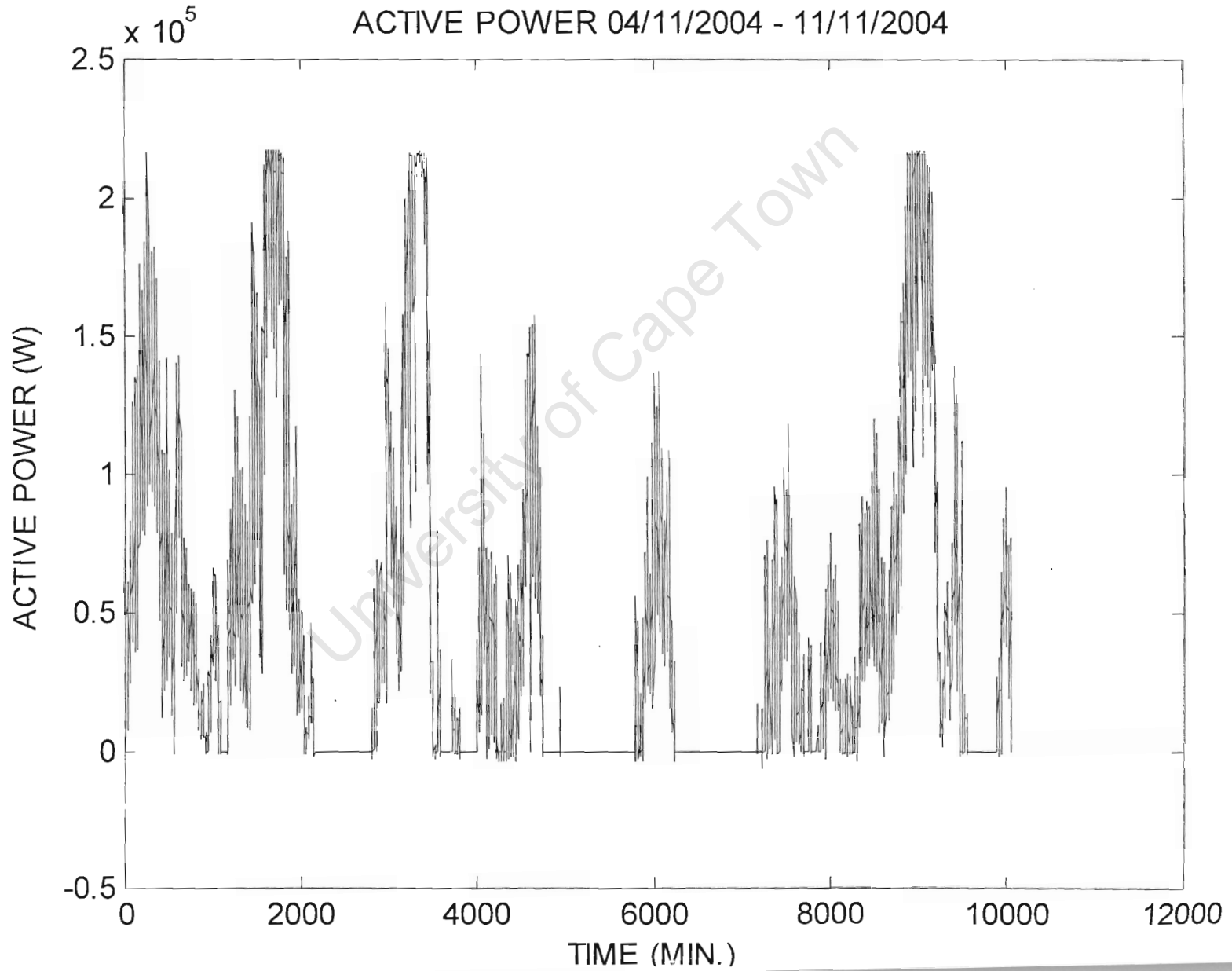
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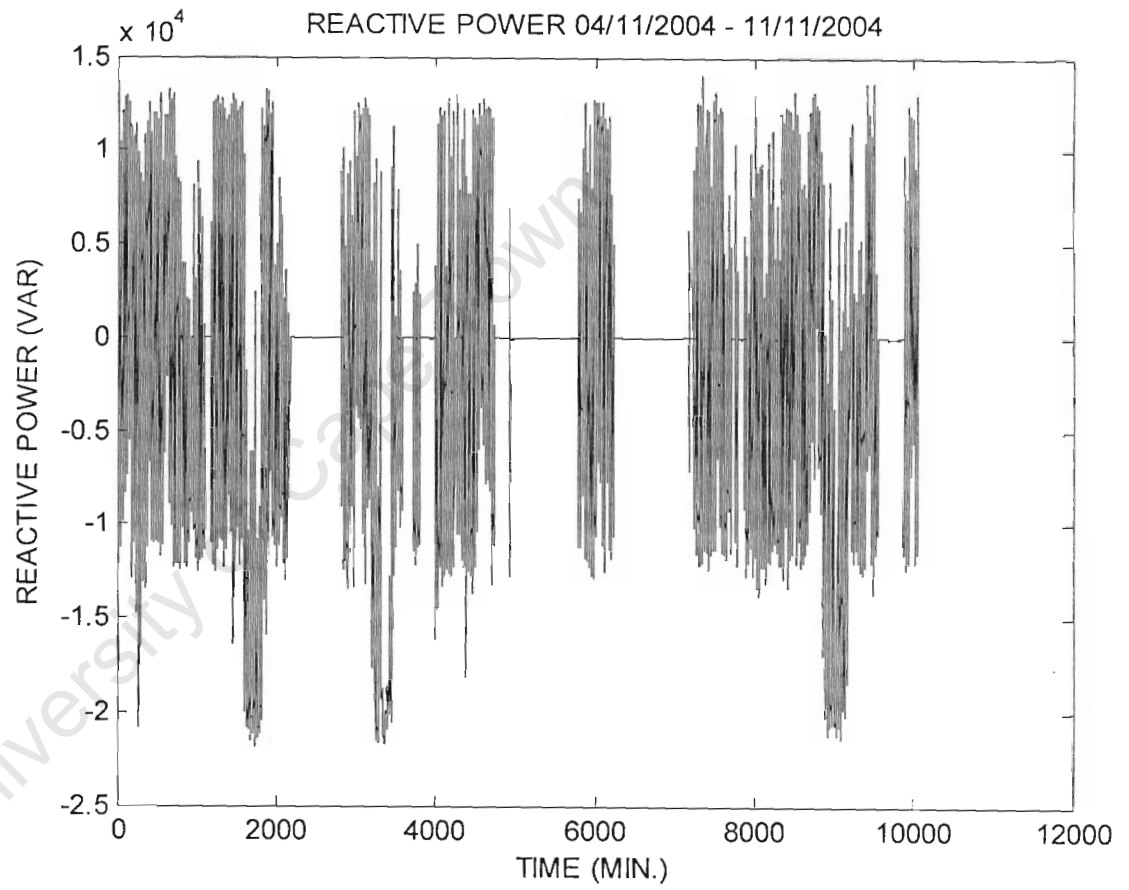


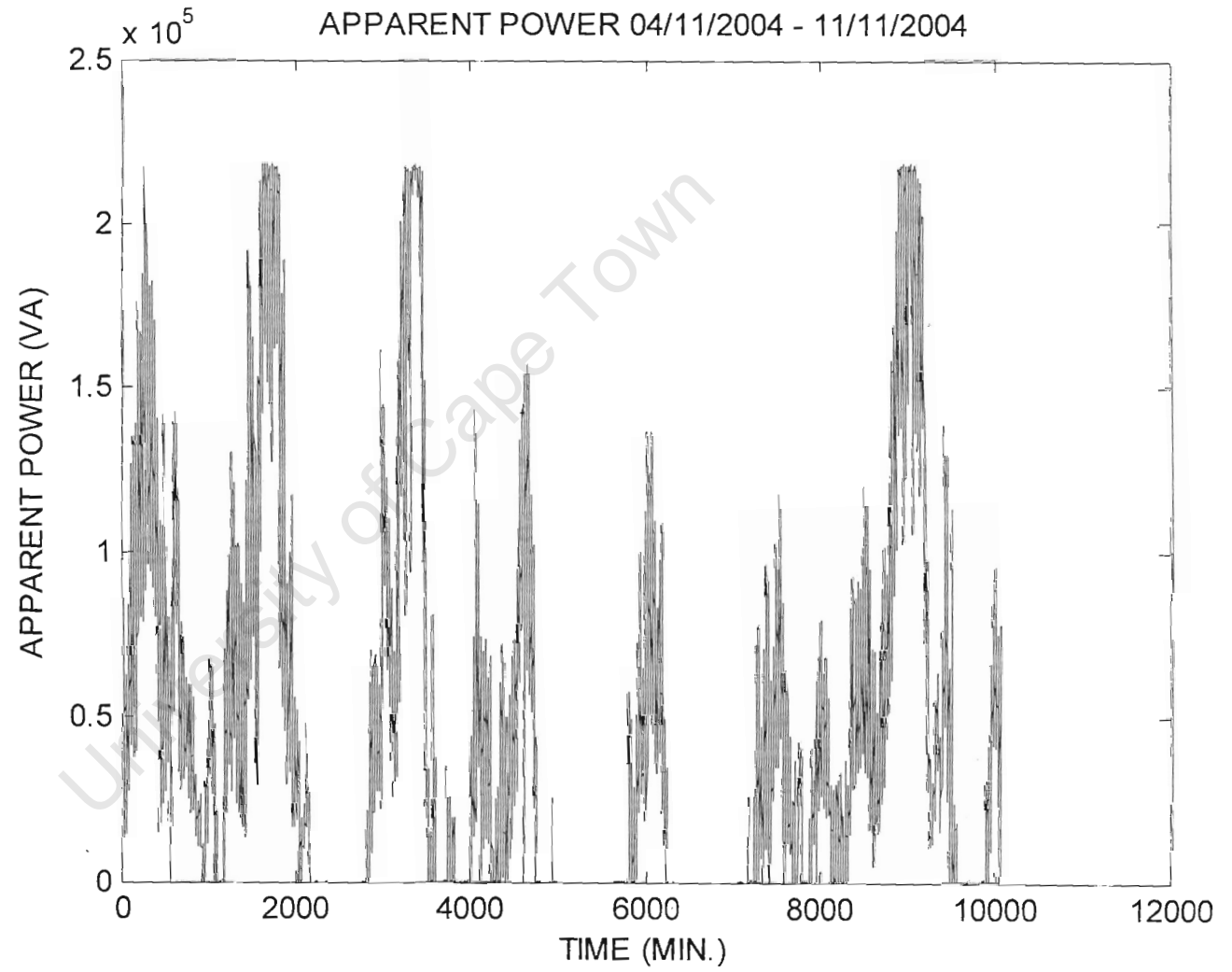
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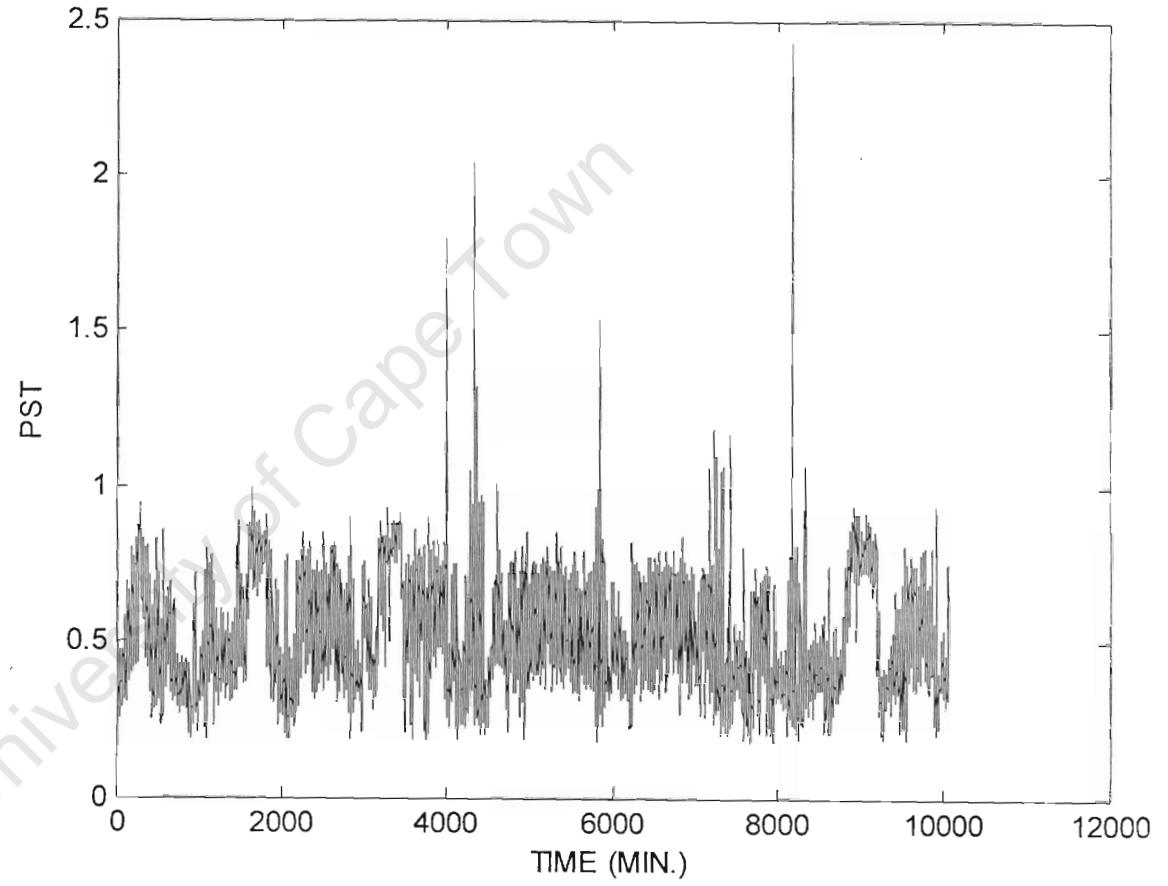
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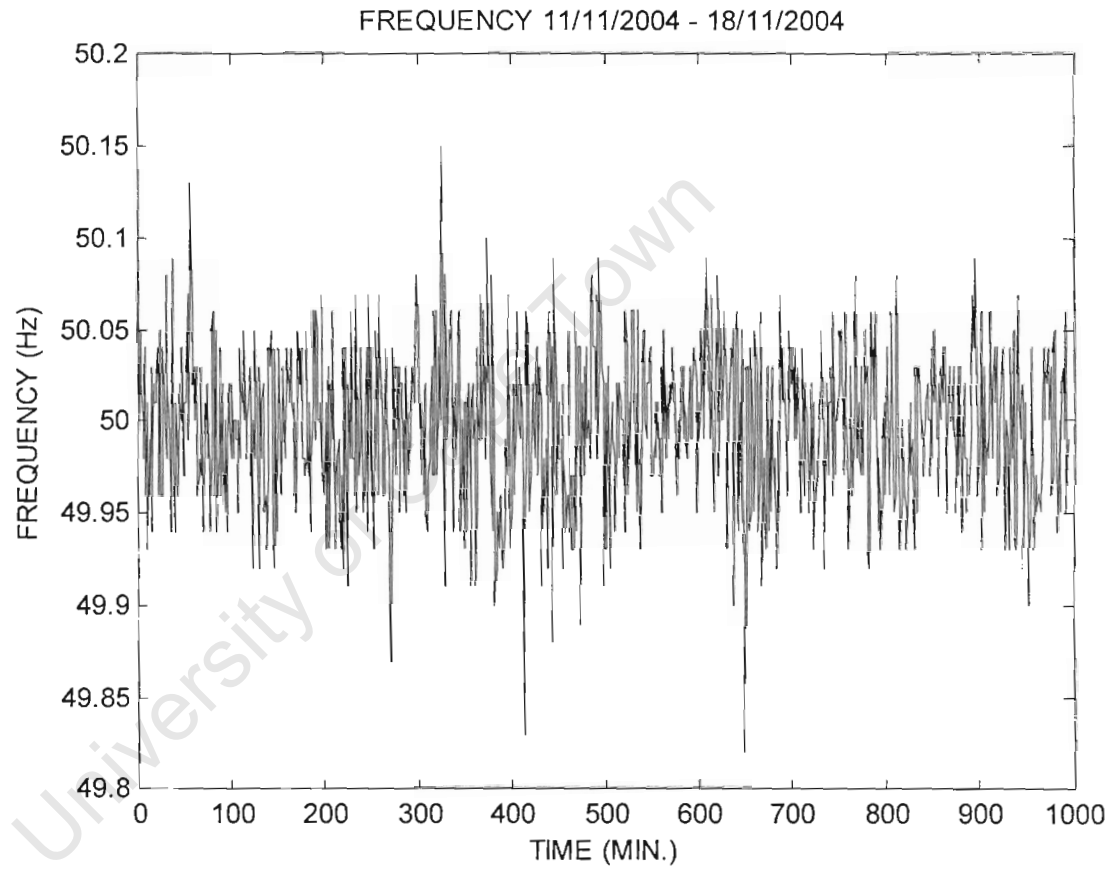




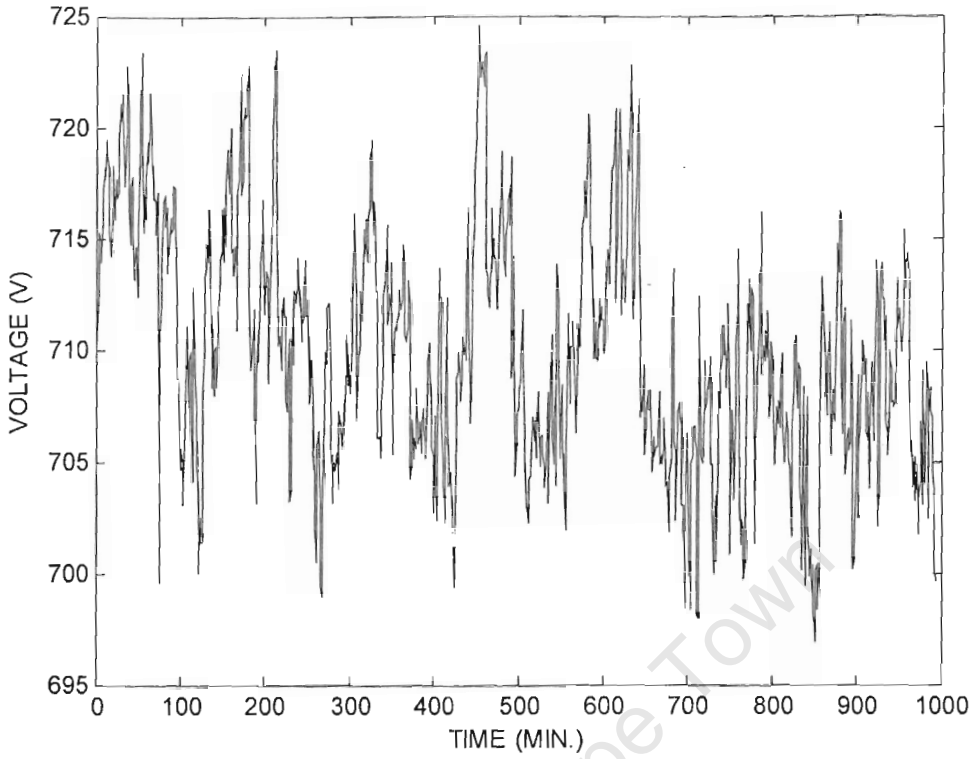


FLICKER 04/11/2004 - 11/11/2004

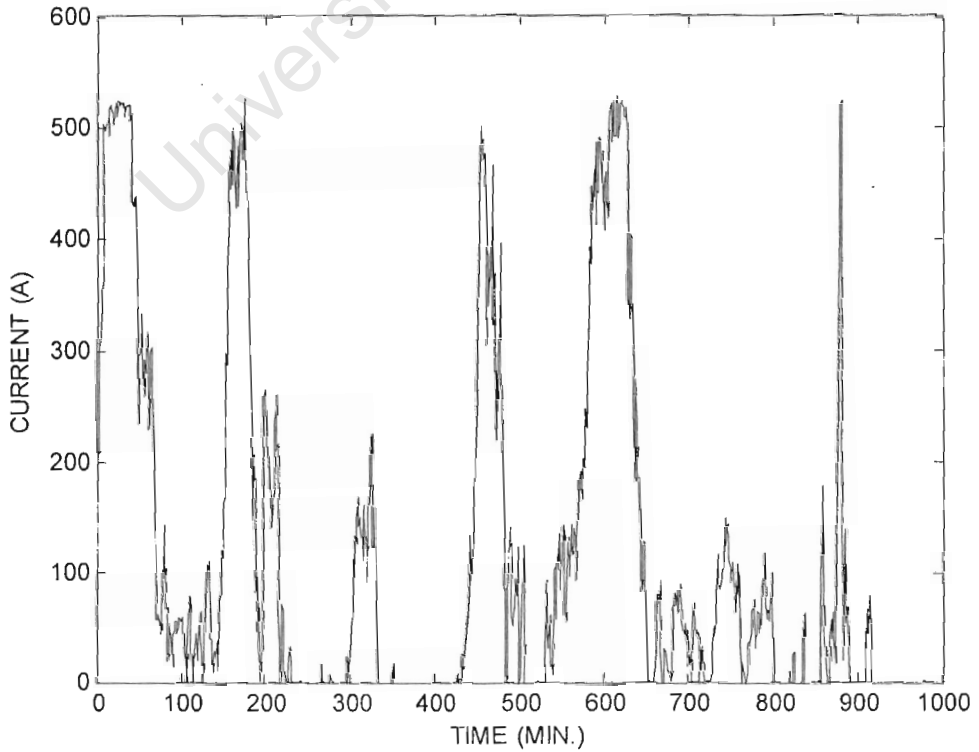


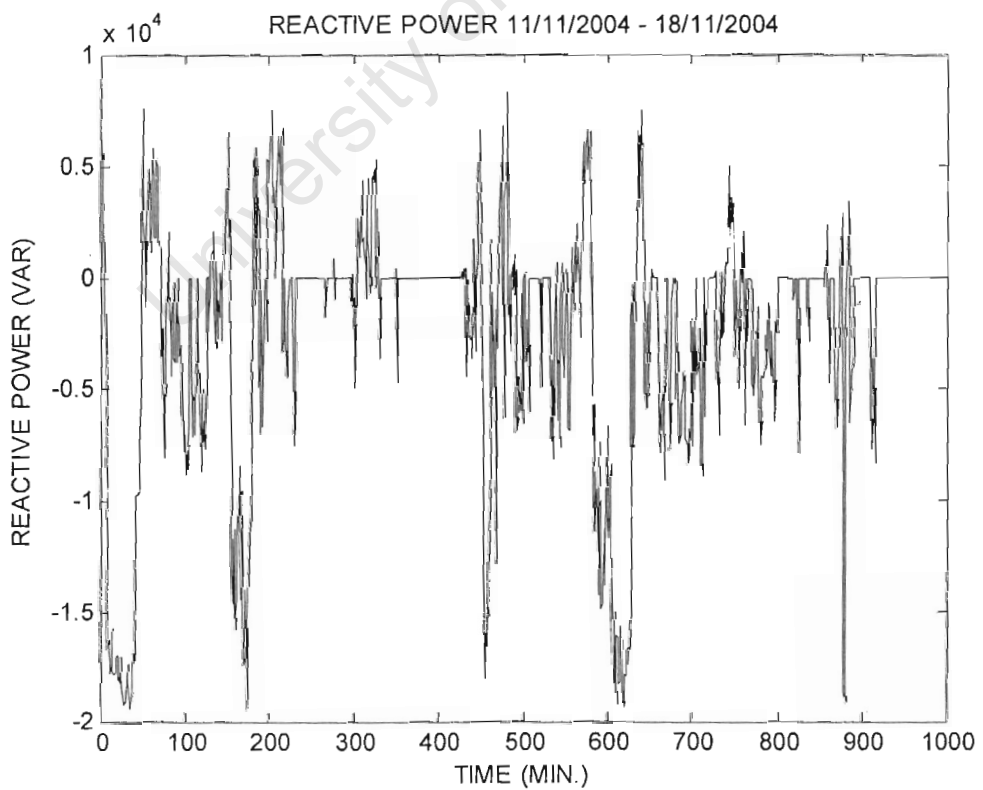
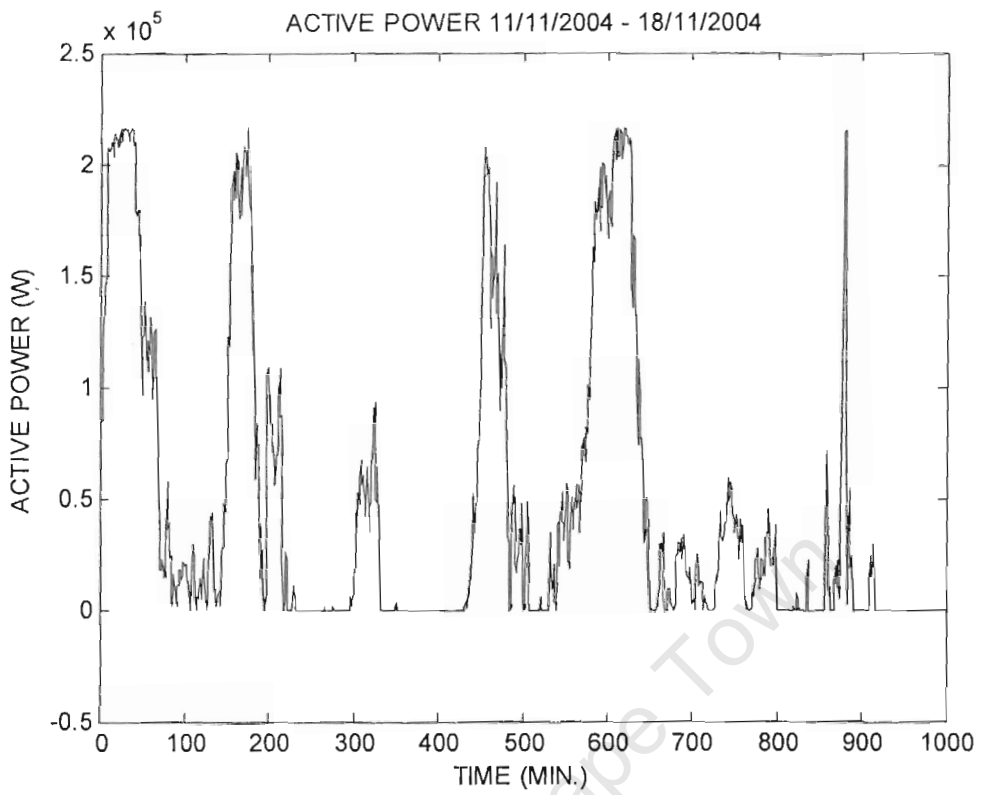


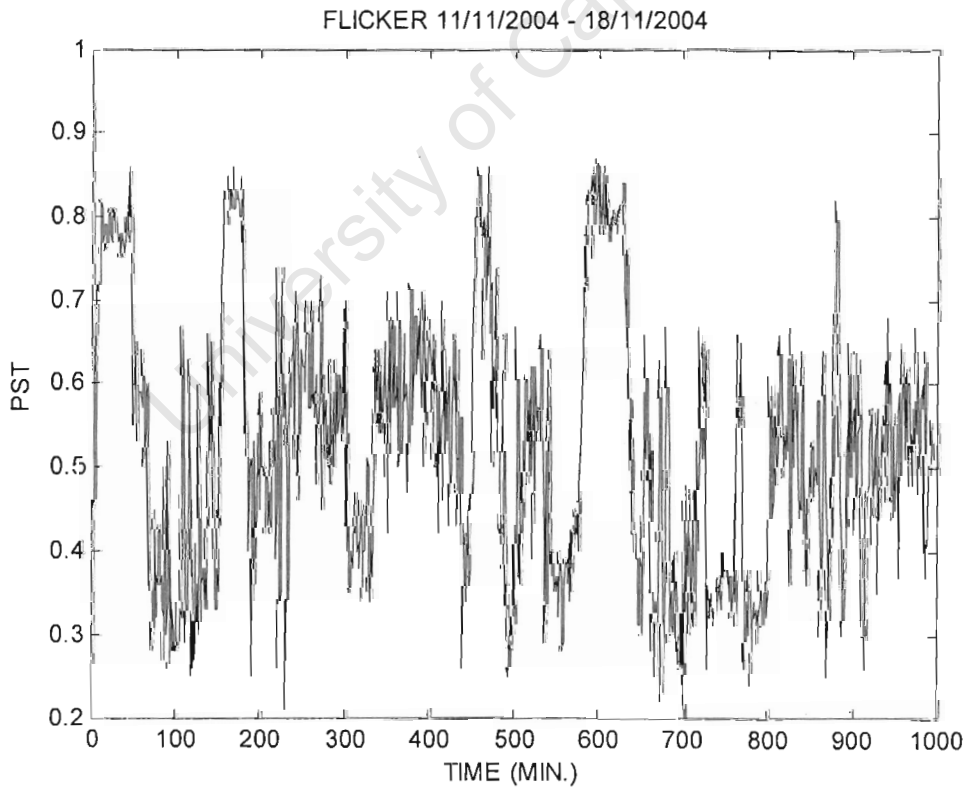
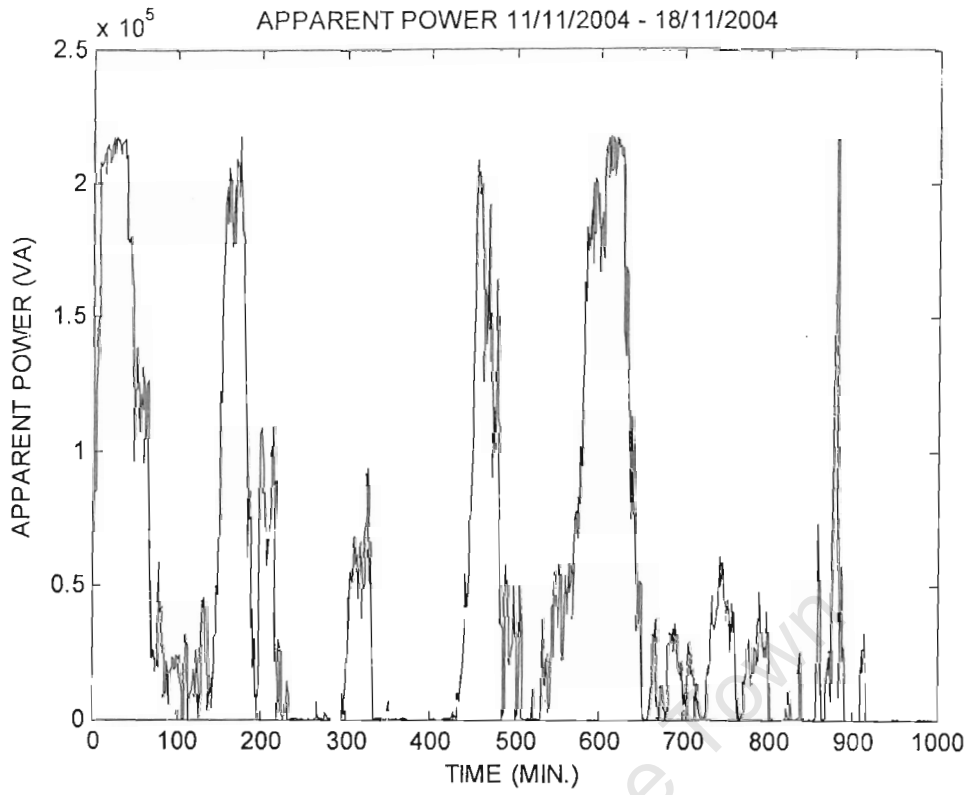
VOLTAGE 11/11/2004 - 18/11/2004



CURRENT 11/11/2004 - 18/11/2004







## APPENDIX B

### ELECTRICAL DATA FOR CASE STUDY 1 AND SIMULATION RESULTS

#### Induction Generator

Voltage	11kV
Power Factor	0.8
Active Power	1MW
Frequency	50Hz
X/R ratio varied from 0.5 to 2	

**X/R = 0.5**

Pgen. (MW)	Qgen. (MVar)	Vpcc (kV)	$\angle_{pcc}$ (°)
1	-0.68	11.49	1.46
0.9	-0.61	11.47	1.30
0.8	-0.54	11.46	1.16
0.7	-0.49	11.44	1.04
0.6	-0.44	11.42	0.92
0.5	-0.4	11.40	0.80
0.4	-0.37	11.38	0.71
0.3	-0.35	11.36	0.62
0.2	-0.33	11.34	0.54
0.1	-0.32	11.32	0.46
0	-0.31	11.29	0.39

**X/R = 0.75**

Pgen. (MW)	Qgen. (MVar)	Vpcc (kV)	$\angle$ pcc ( $^{\circ}$ )
1	-0.68	11.44	1.65
0.9	-0.61	11.43	1.47
0.8	-0.54	11.42	1.31
0.7	-0.49	11.40	1.17
0.6	-0.44	11.39	1.03
0.5	-0.40	11.37	0.90
0.4	-0.37	11.36	0.78
0.3	-0.35	11.34	0.66
0.2	-0.33	11.32	0.56
0.1	-0.32	11.30	0.46
0	-0.31	11.28	0.36

**X/R = 1**

Pgen. (MW)	Qgen. (MVar)	Vpcc (kV)	$\angle$ pcc ( $^{\circ}$ )
1	-0.68	11.40	2.09
0.9	-0.61	11.40	1.87
0.8	-0.54	11.39	1.67
0.7	-0.49	11.38	1.47
0.6	-0.44	11.37	1.29
0.5	-0.4	11.35	1.12
0.4	-0.37	11.34	0.96
0.3	-0.35	11.32	0.81
0.2	-0.33	11.30	0.66
0.1	-0.32	11.28	0.52
0	-0.31	11.25	0.39

**X/R = 2**

Pgen. (MW)	Qgen. (MVar)	Vpcc (kV)	L <sub>pcc</sub> (°)
1	-0.69	11.22	3.40
0.9	-0.61	11.24	3.03
0.8	-0.54	11.25	2.69
0.7	-0.48	11.25	2.37
0.6	-0.44	11.26	2.06
0.5	-0.40	11.25	1.76
0.4	-0.36	11.24	1.47
0.3	-0.34	11.23	1.19
0.2	-0.32	11.22	0.91
0.1	-0.31	11.20	0.65
0	-0.31	11.18	0.39

### CALCULATED POWER FROM MEASURED WIND SPEED

THE RESULTS WERE OBTAINED, USING THE EQUATION:  $P = \frac{1}{2} C_p \rho V^3 A$

Time (Hrs)	Measured Wind Speed (m/s)	Measured Power (W)	Calculated Power (W)
12:00:00	3.419733	0	16999.7
13:00:00	3.319883	2605	15553.7
14:00:00	4.077685	11328	28820.8
15:00:00	5.051036	33180	54778.1
16:00:00	5.8702	45092	85985.3
17:00:00	5.698104	24639	78642.4
18:00:00	5.419375	1306	67657.1
19:00:00	3.546626	64113	18963.2
20:00:00	1.719476	41237	2160.99
21:00:00	1.648719	18579	1905.04
22:00:00	2.091732	144.45	3890.3
23:00:00	2.983434	-1.2413	11287.9
0:00:00	2.601115	-1.27	7480.73
1:00:00	3.026226	-1.3944	11780.7
2:00:00	3.014766	4742.8	11647.3
3:00:00	3.981541	10056	26829.9
4:00:00	4.426271	-38.197	36862
5:00:00	4.378847	-2.0246	35689.9
6:00:00	4.059833	1448.5	28444
7:00:00	4.235085	1144.5	32288.8

8:00:00	5.607301	-4.2821	74942.3
9:00:00	5.53183	4020.3	71956.8
10:00:00	3.979044	-39.945	26779.5
11:00:00	2.768122	567.7	9016.15
12:00:00	6.657029	22163	125403
13:00:00	8.276528	49318	240996
14:00:00	6.101758	86029	96567.4
15:00:00	4.180048	190150	31046.3
16:00:00	6.351733	208530	108929
17:00:00	7.479594	208090	177869
18:00:00	8.034838	194570	220494
19:00:00	6.596262	187310	122000
20:00:00	6.506102	196350	117065
21:00:00	5.764665	143660	81430.6
22:00:00	3.852379	50868	24302.6
23:00:00	3.968338	31104	26563.9
0:00:00	3.649965	17324	20669.6
1:00:00	2.878763	18710	10141.1
2:00:00	2.241938	29677	4790.01
3:00:00	3.865931	14348	24560
4:00:00	4.336787	9616.7	34671.3
5:00:00	3.482496	2303.1	17953
6:00:00	2.385701	11099	5771.83
7:00:00	1.643861	11566	1888.26
8:00:00	1.512063	1148.8	1469.52
9:00:00	2.567746	-0.64293	7196.5
10:00:00	3.705949	-0.71191	21635.4
11:00:00	1.484152	0	1389.63
12:00:00	1.461727	0	1327.59
13:00:00	1.548043	0	1576.94
14:00:00	1.725178	-1.3763	2182.56
15:00:00	2.284108	-1.9617	5065.42
16:00:00	3.620663	-2.605	20175.8
17:00:00	5.608948	6017.7	75008.4
18:00:00	5.208742	18772	60070.9
19:00:00	3.924031	80335	25684
20:00:00	2.133097	69075	4125.7
21:00:00	1.241146	53815	812.708
22:00:00	1.715001	14826	2144.17
23:00:00	1.912301	6836.4	2972.58
0:00:00	2.250241	27669	4843.43
1:00:00	2.27234	17617	4987.53
2:00:00	1.692001	32396	2059.05
3:00:00	1.786071	27765	2421.93
4:00:00	2.064556	42001	3740.64
5:00:00	1.669158	38554	1976.78
6:00:00	1.958148	32819	3191.55
7:00:00	2.165823	25643	4318.51
8:00:00	2.32456	26347	5339.34

9:00:00	3.293855	35693	15190.7
10:00:00	4.899556	56403	49996.1
11:00:00	5.756466	83039	81083.7
12:00:00	6.555	71372	119725
13:00:00	8.886654	84546	298319
14:00:00	10.09815	153330	437714
15:00:00	10.1226	199550	440902
16:00:00	9.310807	139990	343105
17:00:00	8.627901	201320	273012
18:00:00	8.422682	214820	253990
19:00:00	7.690816	213980	193367
20:00:00	4.768216	214290	46082.2
21:00:00	3.537797	197640	18821.9
22:00:00	3.62417	156290	20234.4
23:00:00	3.324548	51025	15619.4
0:00:00	2.151098	50017	4231.03
1:00:00	2.352275	52670	5532.61
2:00:00	1.210596	83890	754.159
3:00:00	1.361815	22178	1073.54
4:00:00	2.331502	-3.371	5387.32
5:00:00	2.550369	8139.1	7051.39
6:00:00	2.334359	16903	5407.15
7:00:00	2.836149	2180	9697.34
8:00:00	1.537895	6158.4	1546.13
9:00:00	1.043371	-4.1309	482.817
10:00:00	1.253339	-1.3881	836.896
11:00:00	1.808559	0	2514.57
12:00:00	2.111217	0	4000.04
13:00:00	3.059695	-1.3706	12175.9
14:00:00	3.341992	-4.506	15866.5
15:00:00	4.377055	-2.4395	35646.1
16:00:00	4.44032	4807.7	37214.2
17:00:00	6.212163	43760	101905
18:00:00	6.086986	45871	95867.7
19:00:00	5.711165	33637	79184.4
20:00:00	4.123188	41793	29796.5
21:00:00	2.461161	27199	6337.03
22:00:00	4.044758	4844.8	28128.3
23:00:00	2.8086	3729.8	9417.49
0:00:00	3.819278	10570	23681.5
1:00:00	3.91883	248.11	25582
2:00:00	4.367097	-5.9534	35403.3
3:00:00	4.426357	-3.4912	36864.2
4:00:00	3.756942	-2.0324	22540.8
5:00:00	3.857305	0	24395.9
6:00:00	3.725383	130.42	21977.5
7:00:00	4.189523	18903	31257.9
8:00:00	5.361527	1040.6	65513.6
9:00:00	6.60364	9076.8	122577

10:00:00	6.564719	5599.3	120258
11:00:00	6.635744	10553	124204
12:00:00	7.773516	25593	199672
13:00:00	9.420946	17589	355426
14:00:00	8.11953	-2.4685	227540
15:00:00	9.455601	0	359363
16:00:00	11.01681	-4.0544	568372
17:00:00	10.91455	-1.3546	552691
18:00:00	10.88609	-1.964	548380
19:00:00	9.409028	-2.0789	354079
20:00:00	7.375053	426.12	170514
21:00:00	4.867987	16876	49035.9
22:00:00	4.382824	16362	35787.2
23:00:00	3.876166	23679	24755.6
0:00:00	6.182604	9636.5	100457
1:00:00	3.208561	15215	14041
2:00:00	2.429067	35483	6092.34
3:00:00	1.534657	30454	1536.38
4:00:00	2.285738	21126	5076.27
5:00:00	2.145757	-46.109	4199.59
6:00:00	1.759424	57077	2315.14
7:00:00	1.172162	166500	684.586
8:00:00	2.129642	110710	4105.68
9:00:00	2.196205	17108	4502.81
10:00:00	1.650319	33753	1910.6
11:00:00	2.233255	117290	4734.57
12:00:00	2.883211	152970	10188.1
13:00:00	2.617145	137850	7619.89
14:00:00	3.457904	120740	17575.4
15:00:00	5.91202	87858	87836.1
16:00:00	6.259368	38253	104245
17:00:00	6.148141	14124	98786.4
18:00:00	5.308114	47321	63575
19:00:00	4.667525	4285	43224.1
20:00:00	3.085942	1367.3	12491.9
21:00:00	2.175541	20285	4376.91
22:00:00	3.062066	39113	12204.2
23:00:00	1.665445	44901	1963.61
0:00:00	2.057157	10454	3700.56
1:00:00	3.015422	11676	11654.9
2:00:00	1.718348	-1.3972	2156.75
3:00:00	0.590669	-1.4097	87.599
4:00:00	1.269459	-1.3676	869.604
5:00:00	3.633971	0	20399
6:00:00	3.451591	-1.3067	17479.3
7:00:00	3.788023	-0.65418	23104.9
8:00:00	3.895816	-1.288	25134
9:00:00	3.997395	-1.9021	27151.7