INTEGRATED ENERGY STORAGE-WIND ENERGY CONVERSION FOR THE MITIGATION OF POWER QUALITY PROBLEMS

by

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DECLARATION

I, Mlondolozi Limaphi, declare that the contents of this dissertation/thesis represent my own unaided work, and that the dissertation/thesis has not previously been submitted for academic examination towards any qualification. Furthermore, it represents my own opinions and not necessarily those of the Cape Peninsula University of Technology.

Signed

12 November 2021

Date

ABSTRACT

The study presented in this thesis was conducted to investigate the power quality of wind turbines installed at Dassiesklip Wind Farm and the impacts they could have on distribution networks. The key emphasis is on flicker and voltage fluctuations as grid connected wind turbines could have enormous effect on them, particularly when they are connected to weak distribution networks. Thereby, proposed an introduction of energy storage system as one of the solutions to mitigate the identified power quality problems.

The main objectives and the outline of the thesis are:

- To review existing information on power quality of wind turbines and the effects they could have on distribution networks.
- To study different types of wind turbines and their behaviour.
- To conduct and analyse power quality studies of wind turbines
- To study energy storage and their contribution to power quality problems
- To draw conclusions based on studies conducted

Voltage flicker was identified as the main issue that affects the power quality of wind turbines due to fluctuations in wind turbines power output. Therefore, the study has been carried out specifically on flicker emission by wind turbines to show how it affects the power quality of the distribution networks where wind turbines are connected.

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 results to voltage dips. Capacitor switching is followed by high frequency inrush currents, which could result to transient.

The wind turbine distributed generator was modelled in DigSilent power factory with and without the inclusion of battery energy storage to mitigate the effect of power quality in the distribution network. Thereafter, load flow studies were carried on the developed models to determine the effect of RMS fluctuations and transient events.

Based on the results obtained, it was discovered that at low X/R ratios, the voltage variations are high and the voltage at PCC increases with an increase in active power generated by the wind turbine induction generator when no energy storage system was connected. However, this voltage increase is low at high X/R ratios, because the active power generated by the generator result to a voltage surge caused by the grid resistance. However, the inclusion of energy storage (battery storage) provides a rapid response for either charging or discharging the battery and also acts as a constant voltage source for the critical load in the distributed network, thus provided a better power quality.

It can be concluded that the Dassiesklip Wind Farm should easily conform to the harmonic requirements at the 66 kV busbar at Dassiesklip substation with the future fault levels, without any intervention such as shunt capacitors, filters or transformer impedance reduction. The

Wind Farm will conform to the flicker requirements. The wind farm will also meet the rapid voltage change limit if it is assumed to be operating at unity power factor before it is switched off.

The main barriers for widespread commercial implementations of ES with WPPs are high cost of ES technologies, immaturity of some technologies and uncertainty over the quantified benefits. Government subsidies for ES would also speed up widespread use of the new ES installations with WPPs.

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GLOSSARY

Terms/Acronyms/Abbreviations	Definition/Explanation
DWF	Dassiesklip Wind Farm
PQ	PQ: Power Quality
PQRM	PQRM: Power Quality Recorder Manager
PQWT	PQWT: Power Quality of Wind Turbines
PCC	PCC: Point of Common Coupling
POC	POC: Point of Connection
QOS	QOS: Quality of Supply
WDN	WDN: Weak Distribution Networks
NRS	NRS: National Regulation Standard
GV	GV: Grid Voltage
DN	DN: Distribution Networks
VF	VF: Voltage Fluctuations
VD	VD: Voltage Dips
PF	PF: Power Fluctuations
WSF	WSF: Wind Speed Fluctuations
TS	TS: Tower Shadow
DS	DS: Distribution Systems
FSWT	FSWT: Fixed Speed Wind Turbines
VSWT	VSWT: Variable Speed Wind Turbines
DL	DL: Data Loggers
EG	EG: Embedded Generators

TRFR	**TRFR: Transformer**
DG	**DG: Distributed Generators**
IG	**IG: Induction Generator**
SOC	**SOC: State of Charge**
ES	**ES: Energy Storage**
ESS	**ESS: Energy Storage System**
WF	**WF: Wind Farm**
EC	**Energy Conversion**
WE	**Wind Energy**
EST	**Energy Storage Technologies**

CHAPTER ONE
INTRODUCTION

The power quality problems due to grid connected wind farms are a common concern extensively, because of the continuous development of wind power generation. The main aspects of power quality problems are voltage fluctuation, flicker and harmonics. Flicker severity may be caused by the fluctuation of wind farm output and grid voltage due to the random fluctuation of wind speed and inherent characteristics of wind turbines. It is important to investigate the impact of power quality on load and operation of power system.

Because the wind doesn't always blow, there has been a significant call for the implementation of energy storage as a critical component of future energy systems that utilize huge quantities of variable renewable resources. Wind power fluctuations have negative effects on power quality, such as system frequency and local voltage. Wind power fluctuations are reduced by integrating energy storage systems (ESS) in a wind farm.

When wind power output drops, grid operators must be able to provide adequate power from other sources to maintain balance between load and generation. Integration of wind power in power grids is confronted with many challenges, including but not limited to elimination or reduction of power fluctuations securing power quality, connection of wind farms to weak grids and estimation of wind power.

This report describes an investigation of the effects of wind power generation on power quality of distribution networks. The main focus is on flicker and voltage fluctuations as grid connected wind turbines can have a significant effect when connected to weak distribution networks. Nine wind turbines have been installed at the Dassiesklip wind farm, in the Western Cape province of South Africa. Practical measurements will be taken for comparison with theoretical studies.

1.1 Statement of Research Problem

Distribution networks are designed to function without generation on the distribution system. Distribution systems were designed to receive bulk power from the transmission system and distribute it to different 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 (Jenkins et al., 2000). 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 (Jenkins et al., 2000). 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 customers 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, connection to distribution networks results in high voltage fluctuations on the network.

Before the bulk of upcoming wind generation is constructed and the system becomes difficult to change, the fast growing deployment of wind generation provides an opportunity to implement proper procedures and technologies instantly. Even though the actual execution has been limited, there has been notable interest in grid level energy storage technology over the past couple of years. Partly, this is due to the fact that energy storage is currently quite expensive, limiting use to critical applications where traditional technologies are not able to offer the essential services at an affordable cost (Zhao et al., 2015). But it is also important to note the fact that most energy storage technologies are new and unproven.

The connection of wind turbines to distribution networks could have an impact on power quality of that particular network.

1.2 Background to the Research Problem

Since the late 1980’s, the term power quality has become one of the most prolific buzzwords in the power industry. Furthermore, the term power quality is an umbrella concept for a number of individual types of power system challenges. The challenges that are covered under this umbrella are not necessarily new. What is new is that engineers are now beginning to deal with these challenges using a system approach rather than dealing with them one by one as individual challenges.

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.

1.3 Research Objectives

Given the challenges stated, a hypothesis that will guide the research was formed.

The hypothesis is stated as follows:

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

The main objectives of the study are:

- To review existing information on power quality of wind turbines and the impacts they could have on distribution networks
- To study different types of wind turbines and their behaviour
- To conduct and analyse power quality studies of wind turbines
- To study energy storage and their contribution to power quality problems
- To draw conclusions based on studies conducted

CHAPTER TWO
LITERATURE REVIEW

Power quality of wind turbines studies 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. The studies also identify 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.

2.1 History and Background of Wind Turbines

Distributed generation is the form of generating electrical energy into distribution networks. Distributed generation is used worldwide 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, photovoltaic, fuel cells and micro generators. Many European countries have been using wind energy to generate electricity since the 19th century (Larsson, 2002).

The first country to use wind turbines to generate electricity is Denmark (Larsson, 2002). Several units with capacity of 5 to 25 kW were in operation by 1910 (Larsson, 2002). 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 (Thiringer et al., 2004). However, there are some common obstacles to wind energy development in Southern Africa such as lack of local manufacturers (about 80% of all wind turbines sold world-wide are manufactured by European countries) (Thiringer et al., 2004).

The use of renewable energy resources has increased dramatically over the past 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.

2.2 Distributed Generation

Distributed generation has far many definitions, varying from country to country. For instance (Jenkins et al., 2000), refers to distributed generation as embedded generation, meaning generation which is connected to distribution network. On the other hand, CIGRE (Jenkins et al., 2000) defines distributed generation as generation that is:

- Not planned centrally,
- Not dispatched centrally,
- Usually connected to the distribution network, and
- 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 (Oelsner, 2002):

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

The South African definition was then defined as follows: (Oelsner, 2002)

"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 Distributed Generation in Southern Africa and worldwide.

2.3 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 type of 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 applies aerodynamic forces that enable the blades to tum 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 (Jenkins et al., 2000):

$$P = \frac{1}{2} . C_p . \rho . A . V^3$$

Equation 2.1

Where:

P = Power in Watts

C_p = 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^2)

Equation 2.1 indicates that the output power rises 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 (Larsson, 1997).

- The turbine blades could be pitched away from the wind mechanically. This method is called pitch regulation.
- 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 (Larsson, 2002). 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, 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.

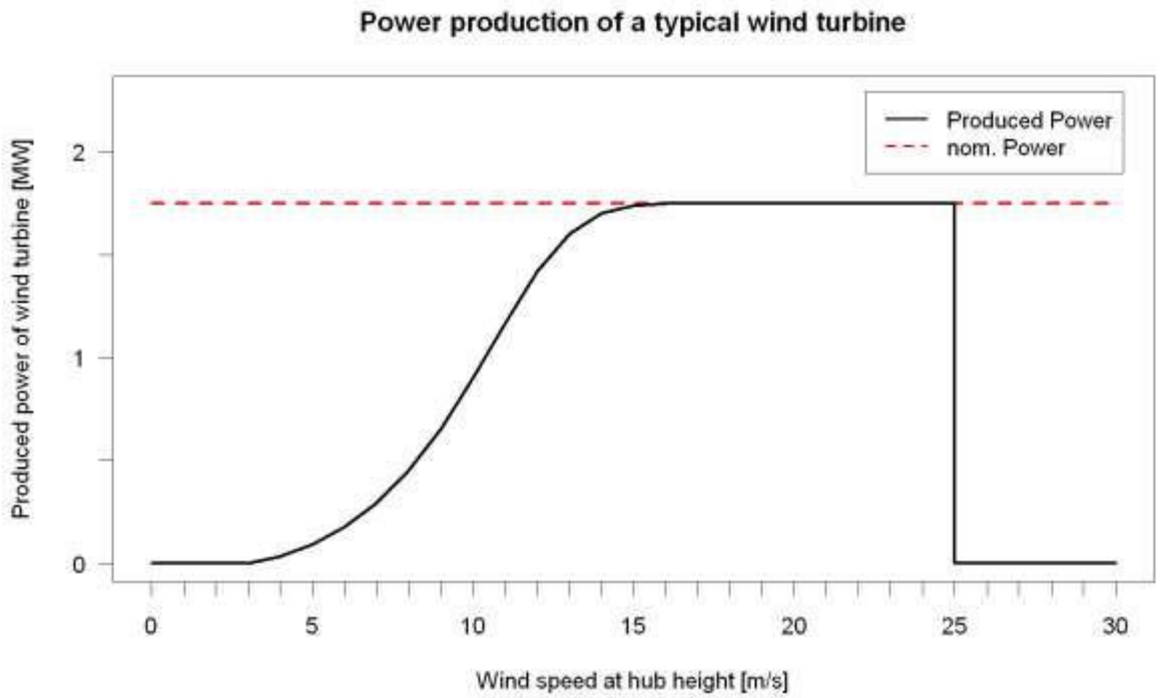


Figure 2.1: **Power Curve (Larsson, 2002)**

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.

2.3.1 Fixed Speed Wind Turbine

Fixed speed wind turbines (FSWT) run at a relatively fixed mechanical speed. These turbines normally employ induction generators that are driven by a turbine through a gearbox and connected directly to the grid. The induction generator runs at an almost constant speed, increasing from the synchronous speed up to a rated speed which is about 1% higher than the synchronous speed (Tande, 2002). 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.

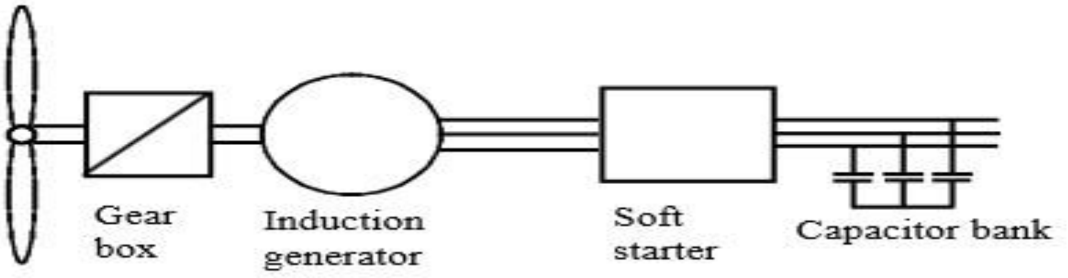


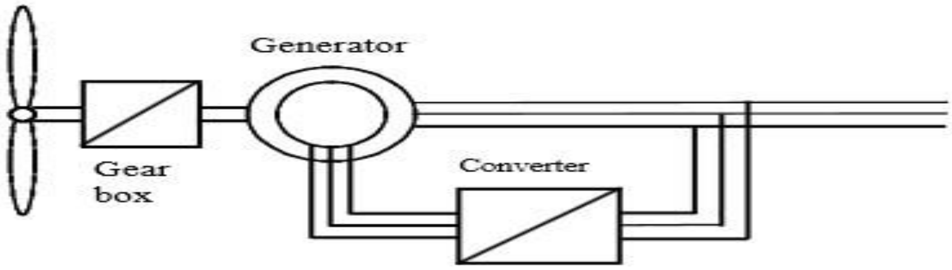
Figure 2.2: **An electrical diagram of a fixed speed wind turbine (Larsson, 2002)**

Fixed speed wind turbines produce power fluctuations as depicted by many researchers like Larsson et al (Larsson, 1997). 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 (Tande, 2002).

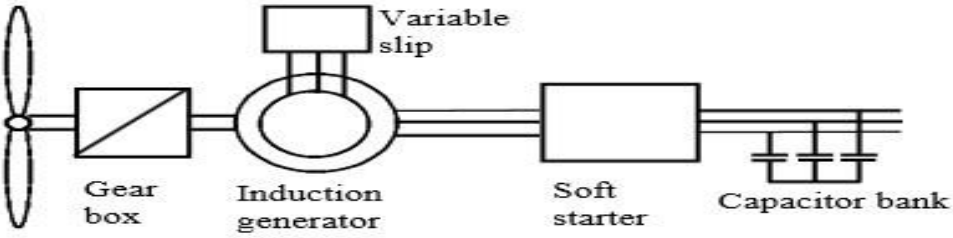
2.3.2 Variable Speed Wind Turbine

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 utilized 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 decrease power fluctuations coming from the tower shadow.

They operate at either a narrow speed range or a broad speed range. The difference between the two is the capability to reduce noise and energy production (Larsson, 2002). A wide speed range rises the power generation and decreases the noise further when compared to a narrow speed range. VSWTs that operate within a narrow speed range are usually 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% (Larsson, 2002).



(a)



(b)

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 (Larsson, 2002)**

A broad speed range wind turbine is equipped with a frequency converter (Larsson, 2002). The utilization of the latter makes the usage of a direct-driven generator possible. Before it is fed into the grid, the alternating current coming from the generator is rectified first then converted into alternating current. An electrical diagram of a broad-speed range wind turbine is shown below. The converter includes both a rectifier and an inverter.

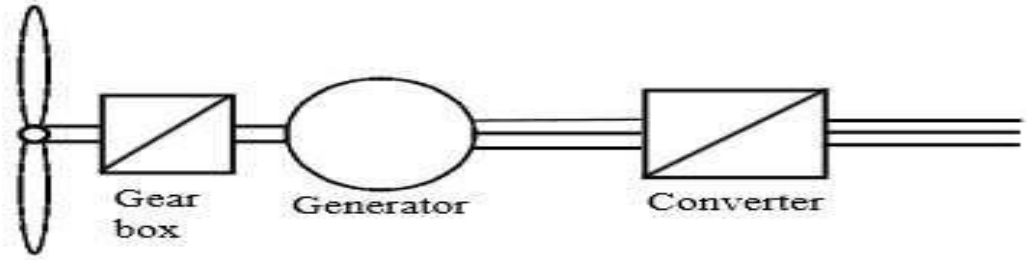


Figure 2.4: **Variable speed wind turbine with a converter (Larsson, 2002)**

2.3.3 Operating Principles of Wind Turbines

Wind turbines function under a very simple principle, which is be defined in a simple context. The energy in the wind turns two or three propeller-like blades around a rotor. The rotor is connected to the main shaft, which spins a generator to produce electricity. Wind turbines are mounted on top of a tower to capture the most energy from the existing wind. Wind Turbines can take advantage of faster and less turbulent wind, at approximately 30 meters or more above ground level. Wind turbines can further be used to generate electricity for a single home or building, or they can be connected to an electricity grid for more widespread electricity distribution (Larsson, 2002).

Wind turbines work the opposite of a fan, as simple stated. Wind turbines use wind to generate electricity, instead of using electricity to produce wind as the fan does. The wind turns the blades, which spin a shaft, which connects to a generator and generate electricity (Larsson, 2002).

2.4 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 (Jenkins et al., 2000). Distribution networks have been passive circuits, supplying the load (Jenkins et al., 2000). 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 (Jenkins et al., 2000). This change in power flow in a distribution system due to the connection of distributed generators has significant technical and economic effects for a power system (Jenkins et al., 2000).

Wind turbines can be standalone 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 (IEA, 2014). Tower shadow effect and turbulence causes voltage fluctuations.
Tower shadow effects are the effects caused by rotating blades. Every time a blade passes the tower, there is a drop in output power. This drop happens 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 (Thiringer, 2002):

- 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.

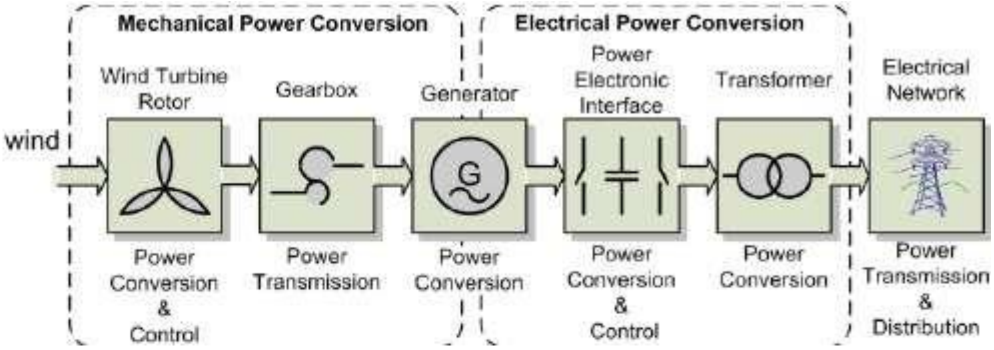


Figure 2.5: **The Connection of Wind Turbines to the Distribution Network (Larsson, 2002)**

2.5 Power Quality

Power provision should be reliable, maintain nominal voltage level, unity power factor, nominal frequency levels and no transients (Thiringer, 2002).

Quality of supply can be affected by several power system conditions. Power system can affect the power system components efficiency and a poor power quality can influence and raise costs of maintenance in the system and produce failures in the different components including motors (Larsson, 2002).

Poor power quality could be caused by rapid variations in generator output. Energy Storage could be a candidate for system support by improving power quality, provide voltage support and aiding in reliable services (Fernão et al., 2014).

Power quality can be important for some industrial customers which can justify the use of energy storage for this purpose. Another option would be a partnership between commercial customers and utilities where both sides benefit from this value (Díaz-González et al., 2012).

2.6 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 (Jenkins et al., 2000). 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 2.6.1 explains voltage flicker and why it is of great concern when wind turbines are connected to the grid.

2.6.1 Voltage Flicker

Voltage flicker is the measure of voltage variations, which may cause turbulences to customers (Larsson, 2002). According to Jenkins et al (Jenkins et al., 2000), voltage flicker defines dynamic variations in the network voltage, which may be triggered 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 (Jenkins et al., 2000). It has been shown that the eye is most sensitive to voltage variations around 10Hz.

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 (Tande, 2002).

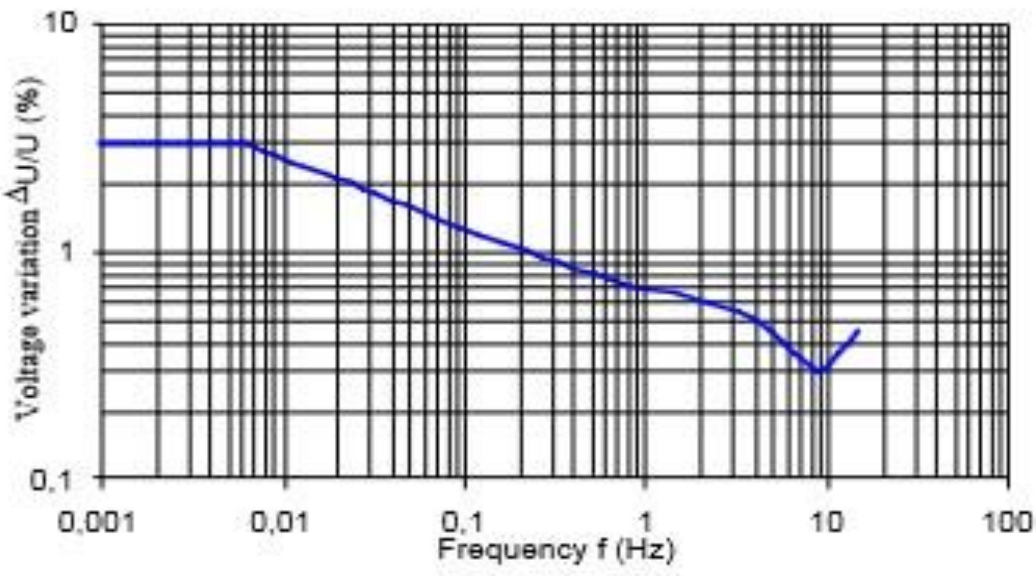


Figure 2.6: **Normalised flicker response for voltage fluctuations (Tande, 2002)**

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

- Often uses relatively large individual items of plant compared to load equipment;
- May start and stop frequently;
- May be subject to continuous variations in input power from a fluctuating energy source. (Jenkins et al., 2000)

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.

2.6.1.1 Flicker during switching operations of wind turbines

Switching operations cause voltage flicker (Larsson, 2002). 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) (Larsson, 2002). 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: (Thiringer et al., 2004)

- The first case is the effect on steady state voltage level during the turbine generator connection. The turbine generator draws high currents, resulting in voltage dips
- The second case is due to capacitor switching. Capacitors are situated in the nacelle. They are used for reactive power compensation. Immediately after the generator is connected to the grid, the capacitor bank is connected. The capacitor bank connection 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 (Tande, 2002).

2.6.1.2 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 (Fernão et al., 2014).

The procedure for assessing flicker emission due to continuous operation assumes that each wind turbine is characterised by a flicker coefficient, which is a measure of the maximum expected flicker emission during continuous operation of the wind turbine (Fernão et al., 2014).

2.7 Energy Storage Technologies

The usage of energy storage to complement wind power has been extendedly investigated and reported in the existing literature. Energy storage is one of the technologies that can be considered to support wind energy integration and offer grid operators with other means for frequency control.

Several articles identify energy storage technologies suitable for wind power application. In (Díaz-González et al., 2012), a review of several storage technologies is made. The authors present operating principle and characteristics of the energy storage technologies and discuss potential applications in wind power.

Although it is impossible to store electricity directly, it can be converted to other forms of energy that can be stored. The stored energy is only converted to electricity when needed. The energy storage systems act as loads during storage and as sources when converting energy back to electric power (Rachel et al., 2013).

Electrical Energy can be stored in energy forms such as mechanical, electrochemical, electromagnetic, thermal and chemical (Zhao et al., 2015), (Rachel et al., 2013).

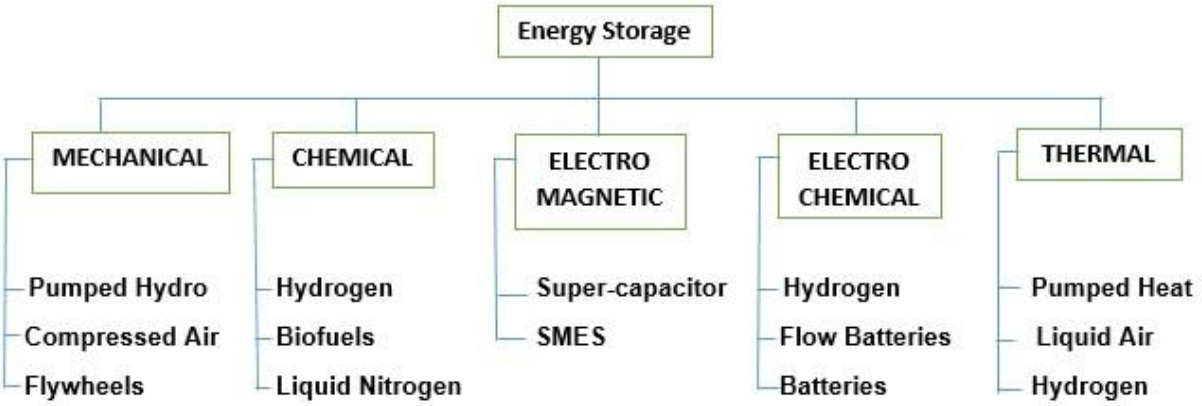


Figure 2.7: **Energy Storage Technologies (Rachel et al., 2013)**

2.7.1 Mechanical Energy storage

Mechanical energy storage technologies are Pumped Hydro Storage (PHS), Compressed Air Energy Storage (CAES) and Flywheel Energy Storage. In PHS, the energy is stored as potential gravitational energy while in CAES, the energy is stored as potential pressure energy. Flywheel energy storage consists of storing energy in the form of rotational kinetic energy. PHS and CAES are considered technologies suited for energy management whereas flywheels are more suitable for power applications.

2.7.2 Chemical Energy Storage

Hydrogen energy storage is a chemical storage technology. Hydrogen is used as an energy carrier for electricity storage through a process such as electrolysis. (IEA, 2014)

2.7.3 Electrochemical Energy Storage

Electrochemical energy storage technologies convert electricity in chemical energy during charging. Batteries are considered electrochemical energy storage systems. (Fernão et al., 2014)

2.7.4 Electrical Field Storage

The energy is stored in magnetic field produced by the flow of direct current. Electromagnetic field energy storage includes Super-capacitors and superconducting magnetic Energy Storage (SMES) technologies.

2.7.5 Chemical Energy Storage Thermal Energy Storage

Thermal energy storage (TES) is a technology that stocks thermal energy by heating or cooling a storage medium so that the stored energy can be used at a later stage for heating and cooling applications and power production. Therefore, TES systems can assist in balancing energy demand and supply on a daily, weekly and even seasonal basis. They can also help in reducing peak demand, energy consumption, CO2 emissions and costs, while increasing overall efficiency of energy systems.

2.7.6 Overview and Comparison of Existing Energy Storage Technologies Worldwide

Table 2.1: Existing Energy Storage Technologies Comparison

Technology	Power [MW]	Energy [MWh]	Efficiency [%]	Lifespan	Installations	Manufacturers
CAES	50 - 300	500 - 2500	64 - 75	40 years	-McIntosh plant, USA, 100MW, 2600MWh -Huntorf plant, Germany, 290MW, 580MWh	Dresser-Rand, Sulzer, Alstom and Turboexpander
FES	1.6	1	80 - 90	20 years	-Usually utilised for UPS - Propulsion applications like engines and road vehicles	Urenco, Teledyne, Pentadyne, Piller, Hitec, Beacon and Active Power
PHES	30 – 4000	500 – 8000	70 - 85	50 years	In more than 240 PHES facilities in the world, there is over 90GW installed	Harris, Water Alchemy, North Am Hydro, Sulzer and Guggler GmbH
SMES	2	0.5 – 5	90 - 99	20 years	-In Wisconsin, a series of distributed SMES units was used to strengthen stability of transmission loop	Intermagnetics General Corporation, Superconductivity Inc, Harc and Accel
					-Several used for power quality control	
SES	1	few seconds	90 – 98	10 years	- Hybrid cars - Power quality applications	NEC, ESMA, EPCOS, Capacitor, NESS and Maxwell
LAES	0.01 - 10	40	75 - 85	Up to 2000 cycles	-VERNON California, 3MW, 4.5MWh -HELCO Hawaii, 10MW, 15MWh -PREPA Puerto Rico, 20MW, 14MWh -CHINO, California, 10MW, 40MWh	-Enersys , GNB (Exide) -C&D Technologies, Hawker Energy (Enersys)
NCES	0.01 - 40	few hours	60 - 70	1000 – 3500 cycles	-Golden Valley, Fairbanks, Alaska 40 MW for 7 minutes	Saft, Alcad

NaSES	200	1200	86 - 89	4500 cycles, up to 15 years	-Hittachi Plant 8MW/58MWh -Rokkasho, Japan 34MW/245MWh	NGK Insulators
ZEBRA	Several MW	Several MWh	90	More than 3000 cycles, up to 10 years	-Stabio, Switzerland 40MWh -mainly in hybrid vehicles	Beta R&D
LIES	Several MW	Several MWh	90 - 95	More than 20000 cycles	-variety of portable electronic devices -there are tests in MW range	BYD, A123 Systems, Li-Tec Battery GmbH, Saft, Lucky Goldstar Chemica and Valence Johnson Control
FBES	Several MW	Several MWh	70 - 80	Up to 10000 cycles, Up to 15 years	-Several installations together with wind turbines -A few installations planned in the near future with WTs	-Prudent Energy -ZBB Energy

2.8 Introduction of Energy Storage on Wind Energy

Energy storage can be utilised to enhance the use of renewable energy. For instance it can be used to eliminate power curtailments and avoid oversized construction of power generation capacity. Energy Storage Systems can further be utilized to store extra renewable energy to be utilized at a different chosen time (Zakeri & Syri, 2015).

The role of Energy Storage System for the wind farm owner would be to make wind farm grid friendly so that it can be controlled like conventional power plants. Energy Storage Systems could be used for time shifting, output smoothing and transmission utilization efficiency (Zhao et al., 2015).

For the grid operator, the Energy Storage Systems could mitigate the unpredictability and uncertainty of the whole grid and not just specific to wind farms. Energy Storage systems could be used for energy arbitrage or load levelling, frequency regulation, inertia emulation, oscillation damping, voltage control support, low voltage through support, reserve application, emergency power supply or black start and transmission utilization efficiency (Zhao et al., 2015).

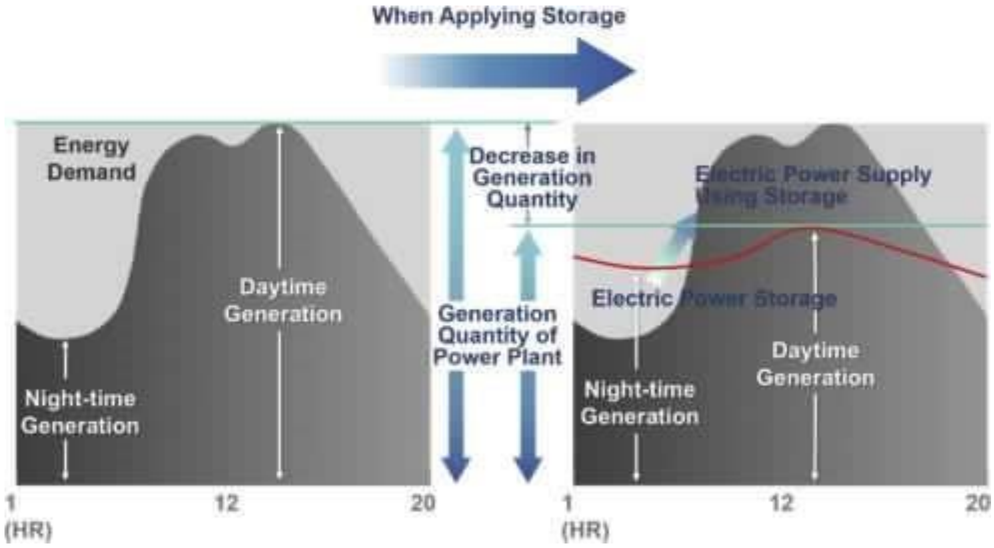


Figure 2.8: **Load Levelling with the Adoption of Energy Storage System (Cho et al., 2015)**

2.8.1 Basic Method of Connecting Energy Storage System to the Wind Farm

The ESS is there to compensate the power fluctuations from the wind farm. The energy storage system is ordered to supply and/or absorb power equal to the fluctuations between the original output of the wind power. Figure 2.9 indicates the topology of a wind farm with ESS.

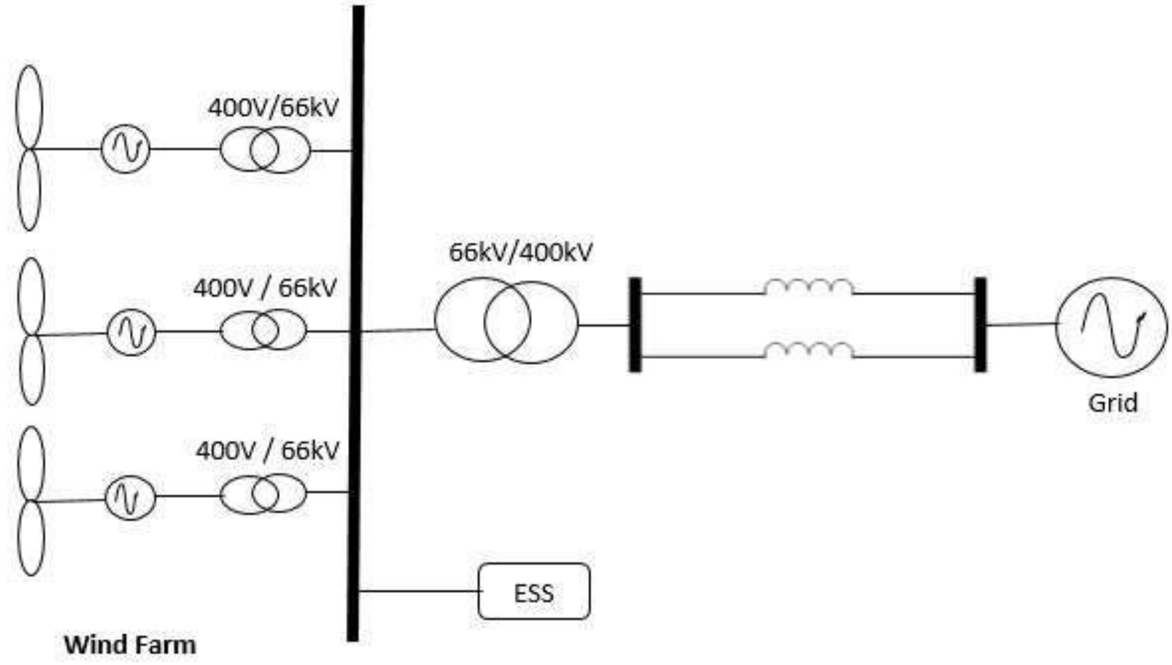


Figure 2.9: **Wind Energy System with Energy Storage System**

The primary capacity of an ESS could be defined by the following equation:

$$E_{ESS} = \sum_{i=1}^{i=N} \left(|P_{WIND}(t_i) - P_{ref}(t_i)| \right) \Delta t$$

Equation 2.2

Where:

$P_{WIND}(t_i)$ is the basic wind power generator output at point

$P_{ref}(t_i)$ is the anticipated output that the ESS combination with the wind power generator that complies with the requirements of grid incorporation at i^{th} point

Δt is the measurement of one sample period

Once the anticipated output P_{ref} is found, the capacity of the ESS can also be determined.

Getting the ideal size of an ESS with the above equation will not be easy. In this study, this problem is transformed to minimalize the square differences between the basic output of wind power generator $P_{WIND}(t_i)$ and the anticipated output $P_{ref}(t_i)$, which can be defined as follows:

$$E'_{ESS} = \sum_{i=1}^{i=N} \left(P_{WIND}(t_i) - P_{ref}(t_i)\right)^2$$

Equation 2.3

This proposition can avoid the trouble of complete value. There will be deviance between the two results, but this proposition is there and can fulfil the need of resolving the problem above. The comprehensive technique is shown below:

$$P_{ref}(t_i) = P_{WIND}(t_i) + P_{ESS}(t_i)$$

$$P_{ref}(t_i) = at_i + b$$

Equation 2.4

Assuming $P_{ref}(t_i)$ is the anticipated output of the combination of wind power generator and energy storage system. When the energy storage system absorbs energy, $P_{ref}(t_i)$ is negative, and when the energy storage system releases energy $P_{ref}(t_i)$ is positive. The term a is the change rate, which relies on the grid connection requirements and the wind power generator restrictions:

$$\sum_{i=1}^{i=N} P_{ESS}(t_i) = \sum_{i=1}^{i=N} \left(P_{WIND}(t_i) - P_{ref}(t_i)\right) = 0$$

Equation 2.5

The ESS need to have constant regulation capability, which means the ESS need to satisfy the necessity of the next structured period at the end of one regulation period. For this deliberation, the absorbed energy of the ESS should be the same as the released energy of the ESS during one structured period. This means the SOC (state of charge) of ESS should be initialized at an appropriate value:

$$E_{ESS} = \sum_{i=1}^{i=N} (P_{WIND}(t_i) - P_{ref}(t_i))^2$$

Equation 2.6

This is the objective function to determine the minimal capacity of the energy storage system. According to the standards of the wind power grid integration, the two fundamental requirements of incorporation are as follows:

- The maximum power fluctuation of one minute is one fifth of the power rating of the wind turbine generator.
- The maximum power fluctuation of ten minutes is two-thirds of the power rating of the wind turbine generator output power.

2.8.2 Energy Storage Technology Overview

One of the characteristics of electricity is that it cannot be stored directly requiring continuously balancing with the demand, this resulting in costly implications. Sufficient generating capacity is essential to match the highest demand level, even though the capacity increase is only necessary for short periods of time and not frequently (Rachel et al., 2013).

Also, due to inability to store electricity, reserve generating capacity must be maintained available as spinning or non-spinning reserves for potential changes in the load or unplanned loss of generation plant (Rachel et al., 2013).

Although it is not possible to store electricity directly, it can be converted to other forms of energy that can be stored. The stored energy is only converted to electricity when needed.

Energy Storage is an essential intermediate between variable energy generation sources and variable loads. Without energy storage, energy generation is enforced to be the same as consumption. The best advantage of energy storage is that it is capable of moving with times (Laboratories, 2013).

From the electrical system viewpoint, the energy storage systems act as loads during storage and as sources of electricity when returning energy to the system (Rachel et al., 2013).

2.8.2.1 Compressed Air Energy Storage

Compressed air energy storage (CAES) is a technological proven means of both storage and power generation that can have exceptional value in combination with alternative power sources such as wind energy.

CAES store energy as elastic potential of compressed air (Evans et al., 2012). CAES is a mature storage technology available for high power and energy capacities. They are suitable for large scale energy storage (Chatzivasileiadi et al., 2013). These characteristics make CAES compete with Pumped Hydro Storage (PHS) (DíazGonzález et al., 2012).

The operation of CAES plants is based on using low cost excess power during offpeak hours to compress air in an underground air tight reservoir. Later, when energy demand is higher, the compressed air is used to supply power to a turbine to generate electricity. CAES are considered hybrid systems as they include storage and generation (Chatzivasileiadi et al., 2013).

CAES systems rely on conventional gas turbine technology (Díaz-González et al., 2012). A CAES includes the following main components: air compressor of two or more stages, intercoolers and after coolers, expanders, gas turbine, a motor or generator, a reservoir for storing compressed air, auxiliary and control systems (Evans et al., 2012).

The principle of CAES is shown schematically in figure 2.10. CAES systems use a motor to compress and store air in an underground carven, the charging mode. During hours of high demand, the compressed air is directed to the surface, preheated and expanded in high and low pressure turbines and introduced in a combustion chamber where it is mixed with natural gas and combusted. The resulting expanding gases are used to drive a gas turbine connected to a generator which produces electricity (Díaz-González et al., 2012).

Compressed air is usually mixed with natural gas for higher efficiencies although it can also be used alone (adiabatic CAES), however with lower energy content (Evans et al., 2012). Other possibilities are the use of synthetic fuels such as gasified biomass and hydrogen instead of natural ones, although the last one is somewhat expensive (Rachel et al., 2013).

CAES deployment potential is area dependent as it requires appropriate geological formations (Chatzivasileiadi et al., 2013). A variety of geological formations can be used in CAES such as solution mined salt caverns, abandoned limestone mines and aquifers. Other options are high quality rock caverns, depleted natural gas storage caverns and salt domes (Karellas & Tzouganatos, 2014). Other feasible alternative to underground caves are underground high pressure pipes (Karellas & Tzouganatos, 2014), aboveground storage tanks (Evans et al., 2012) mechanically formed reservoirs in rock formations (Kousksou et al., 2014) and reservoirs on the seabed (in underwater/ocean CAES) (Akinyele & Rayudu, 2014).

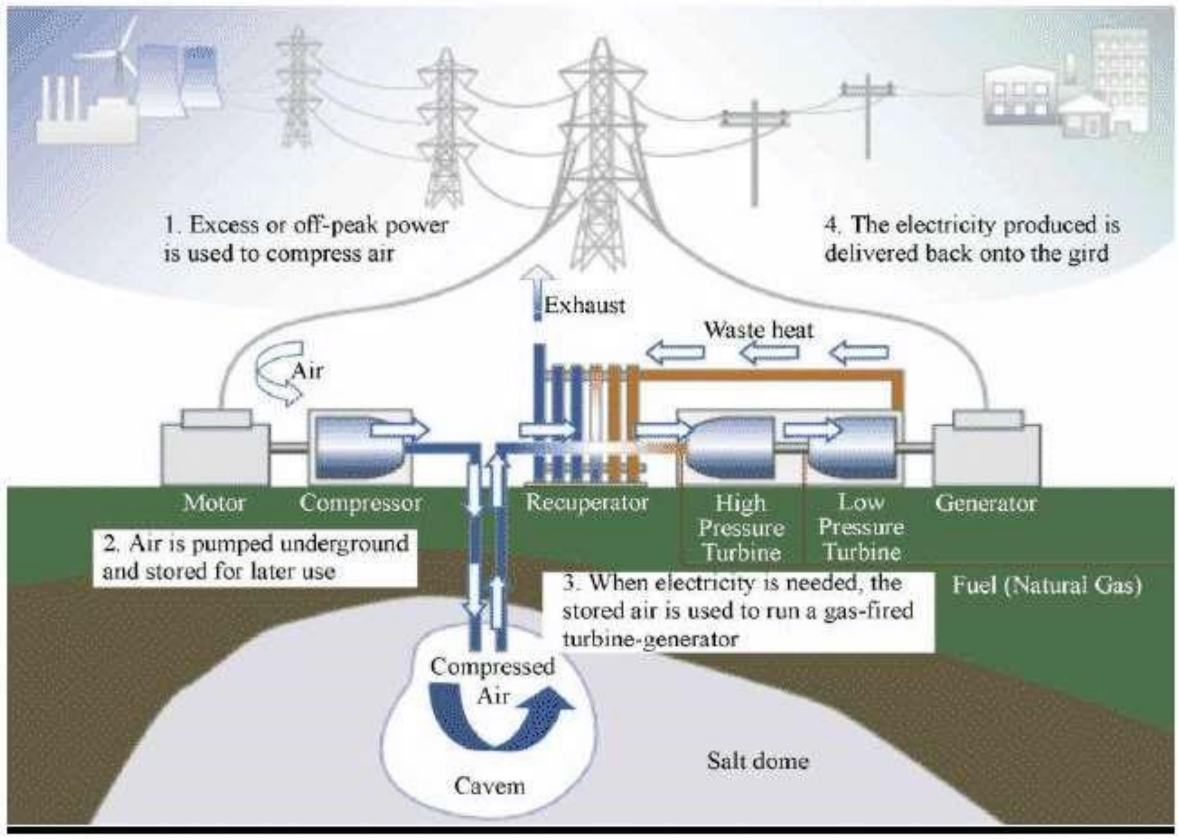


Figure 2.10: **Compressed Air Energy Storage System (Jewitt, 2005)**

2.8.2.2 Pumped Hydro Storage

Pumped Hydro Storage (PHS) have been used since the 1890's being the largest commercially available storage technology and also the oldest (Zhao et al., 2015), (Rehman et al., 2015). The first power plant was built in 1929 (ECOFYS, 2014).

There are over 300 PHS plants around the world totalling to over 127GW and several countries around the globe are planning adding more PHS to power systems to help the use of more renewable energy sources (Rehman et al., 2015). PHS represent nearly 99% of the energy storage capacity installed worldwide (Zhao et al., 2015), ((Rehman et al., 2015).

PHS are characterised by low operation and maintenance, very long life and basically don't have cycling degradation (ECOFYS, 2014). These features set PHS apart from other storage technologies though they have the disadvantage that siting, permitting and environmental impact processes take many years. New opportunities arise for this storage technology in view of higher wind power generation over the next few decades (Laboratories, 2013).

PHS have the advantage that they don't suffer capacity loss in the charge discharge cycle as some other storage technologies (e.g. electrochemical batteries) making them suitable for long discharge and frequent use application (Rachel et al., 2013).

PHS have also been proposed in hybrid energy storage systems in combination with CAES (Kim et al., 2011) and in isolate power production systems (Katsaprakakis et al., 2008).

PHS are considered suitable for wind power integration support although they have geographic restrictions. Current research trends are directed mostly to energy systems for island and mountain regions focusing on wind power support. PHS are used to fill wind power gaps more than in power generation scheduling. Wind and PHS integrated power systems are considered an economically and technically competitive in various geographical areas (Zhao et al., 2015), (Rehman et al., 2015).

Regarding wind energy integration, PHS could address issues related to grid capacity and voltage limits, frequency, network congestion, transmission congestion, harmonics created by wind energy, transient stability, protection, grid stability problems and others (Rehman et al., 2015). PHS could be used for energy management applications through time shifting and also as non-spinning reserve supply (Zhao et al., 2015). Wind-PHS hybrid systems are capable of meeting the hourly demand (Zhao et al., 2015).

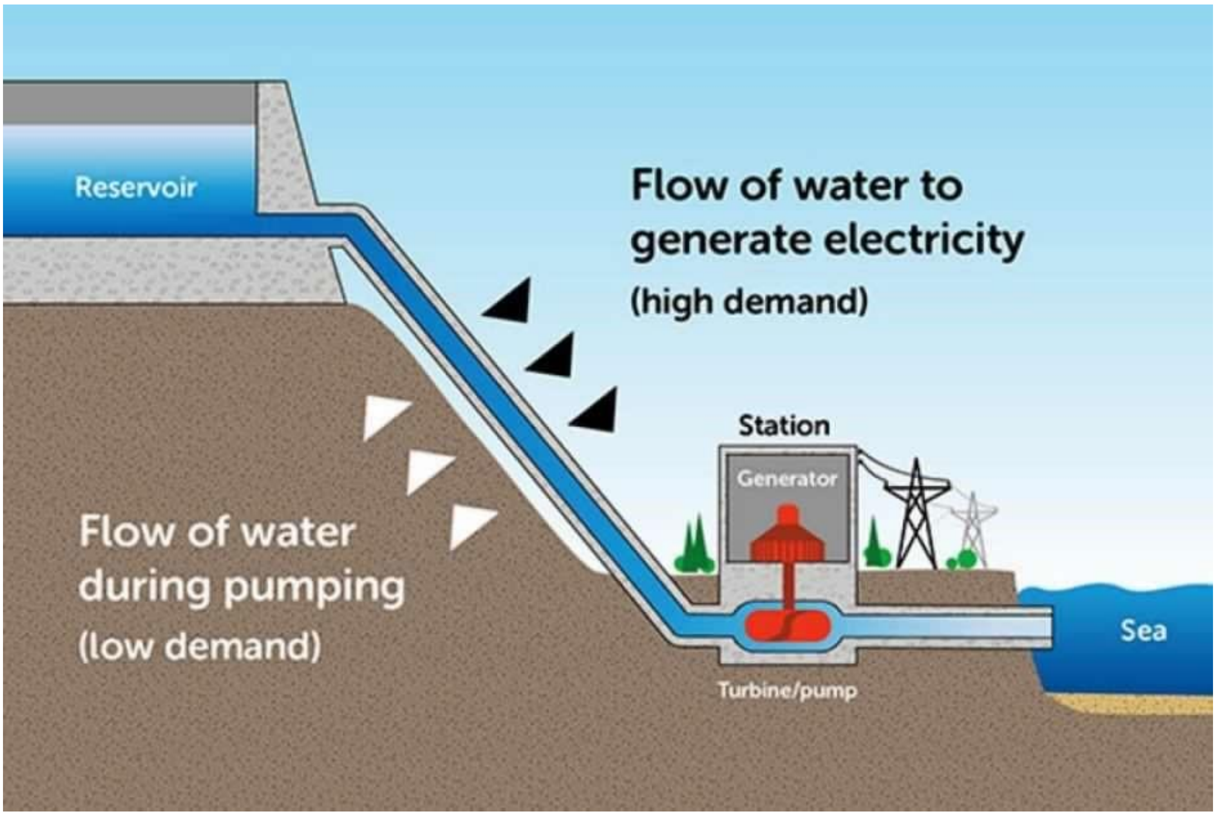


Figure 2.11: **Pumped Hydro Storage System (Luo et al., 2015)**

2.8.2.3 Flywheel Energy Storage

Flywheels energy storage (FES) systems have been available since 1970. The first ones used a large steel rotating body on mechanical bearings (Zhao et al., 2015).

FES store mechanical energy in a rotating flywheel (Suberu et al., 2014). The flywheel spins storing kinetic energy. A bi-directional power converter is needed to transform electrical energy at the machine frequency into DC electrical energy and vice versa. Another bi-directional converter is necessary to transform DC electrical energy to AC electrical energy at grid frequency 50/60 Hz and vice versa (Sebastián & Alzola, 2012). The components of a FES can be seen in figure 2.12. FES usually consists of bearings, an enclosure, a composite or steel flywheel and an electrical machine or motor/generator (Group E.E, 2012).

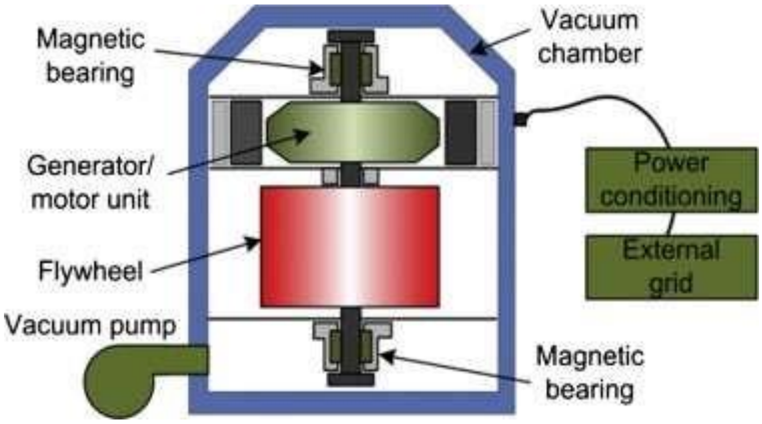


Figure 2.12: **Components of Flywheel Energy Storage (Luo et al., 2015)**

The maximum spinning speed of the flywheel is determined by the capacity of the material to withstand the centrifugal forces. Flywheel materials should not be heavy, with low density and have high tensile strength allowing high spinning speeds. Some example of materials used for flywheels are aluminium, steel, monolithic material, S2 glass, carbon T100, composite materials. Metals are heavy and the spinning speeds are not very high, the energy density obtained being modest. However, metal prices are twenty to thirty times less than composite materials prices. Metal flywheels can be shaped like a disc of Laval or a solid disc, while composite flywheels can be shaped like a thick or a thin ring (Sebastián & Alzola, 2012). Other flywheel shapes are conical disc, flat unpierced disk, thin firm, shaped bar, rim with web, single bar and flat pierced bar (Mahlia et al., 2014).

The electrical machine can act as a generator or as a motor. In generator mode, it slows down the flywheel converting mechanical energy into electrical energy while in motor mode, it speeds up the flywheel consuming electrical energy and increasing its mechanical energy. Variable Reluctance Machines, Permanent Magnet Synchronous Machines and Double fed asynchronous machines have been proposed for FES.

FES are widely used in applications where 24/7 power availability is required in places such as data centres to bridge to the back-up system or to eliminate power outages. Market for FES is focused on selling ancillary services, such as voltage and frequency stabilization, to distribution grids (Energy, 2013).

FES have been proposed in hybrid systems, mostly wind-diesel. A wind-hydrogen plant in Norway at Utsira is equipped with a 200kW Flywheel Energy Storage that is capable to store 5kwh electrical energy for a few seconds (Zakeri & Syri, 2015). FES are suitable for medium scale renewable energy systems (Ramli et al., 2015). FES have also been proposed in a hybrid energy storage system with adiabetic compressed air energy storage for wind power applications (Zhao et al., 2015).

Some of the flywheel energy storage facilities abroad, their characteristics and application areas can be seen on Table 2.2 below.

Table 2.2: **Flywheel Energy Storage Facilities Abroad**

Institutions	Characteristics	Application Area
Active Power Company	Clean Source series 100- 2000kW	UPS systems and Backup power supply
Beacon Power Company	100/150kW per unit, 20MW / 5MW h plant	Power Quality, Frequency regulation and voltage support
Boeing Phantom Works	100kW/5kW h, HT magnetic bearings	Power Quality and peak shaving
Japan Atomic Energy Centre	235MVA, steel flywheel	High power supply to Nuclear fusion furnace
Piller Power Systems Ltd.	3600-1500 rpm, 2.4 MW for 8s	Sources of backup power and Ride through power
NASA Glenn Research Centre	20000-60000 rpm, 3.6MW h	Supply on aerospace aviation and other transports

More FES demonstration plants are needed to prove the suitability of flywheel technology in various applications (European Association for Storage of Energy, 2013).

2.8.2.4 Supercapacitor Energy Storage (SES)

In SES energy is stored in electric field. Principle of operation is not different from that of conventional capacitor; however supercapacitors utilize polarized liquid layers between conducting electrode and conducting ionic electrolyte to increase the capacitance. Due to the fact that capacitance is also reliant on the surface area of electrodes, highly porous material is used in order to increase the area (A Study by the DOE Energy Storage Systems Program, 2001). Supercapacitors can be valued up to 5000F.

SES is having comparable response features and small energy density like FES but they are having small self-discharge ratio and do not have moving parts. They have an ability to mitigate fast wind power fluctuations but with a small time scale. They could be considered as a backing for wind turbines in amalgamation with a battery system instead of standalone.

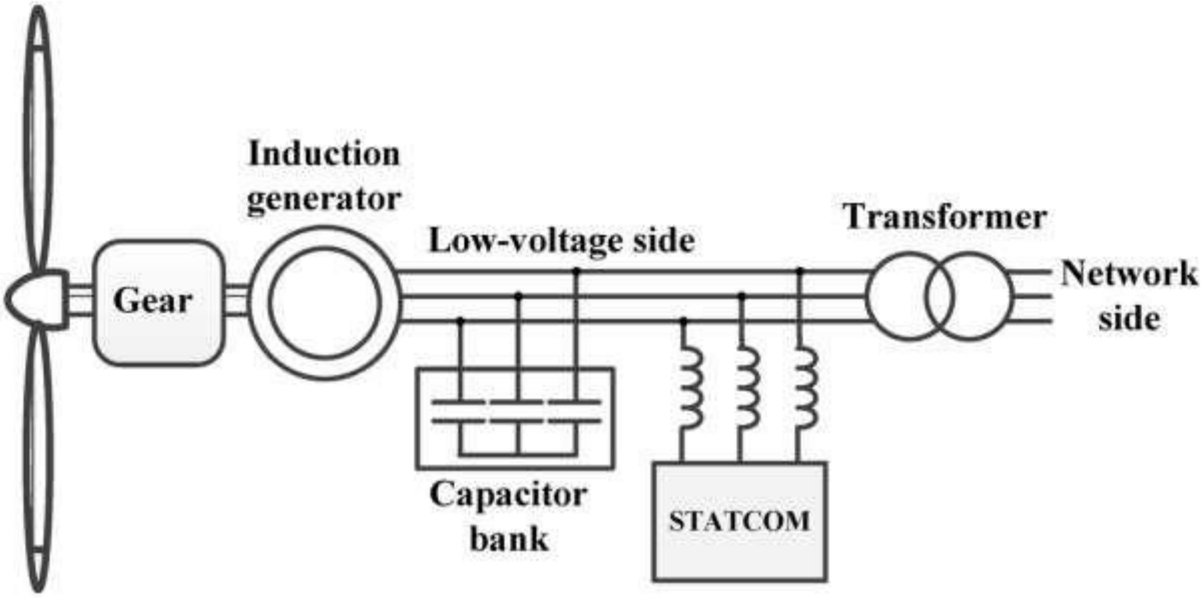


Figure 2.13: **Supercapacitor Energy Storage System (Sebastián & Alzola, 2012)**

2.8.2.5 Superconducting Magnetic Energy Storage (SMES)

SMES stores energy in magnetic field. SMES consists of power conditioning system, superconductive coil, refrigerator and vacuum (Luimnigh & Connolly, 2009). Magnetic field is produced by DC current circulating through a superconducting coil (A Study by the DOE Energy Storage Systems Program, 2001). In order to eliminate resistive losses caused by current flow, the coil is kept in superconducting state. Cooling medium is liquid helium or nitrogen.

SMES are not likely to be used for integrating renewables (Luimnigh & Connolly, 2009). Superconductive coil is excessively sensitive to temperature changes; furthermore SMES has small energy density and power capacity of up to 2 MW.
SMES is nowadays commonly used in industrial power quality market.

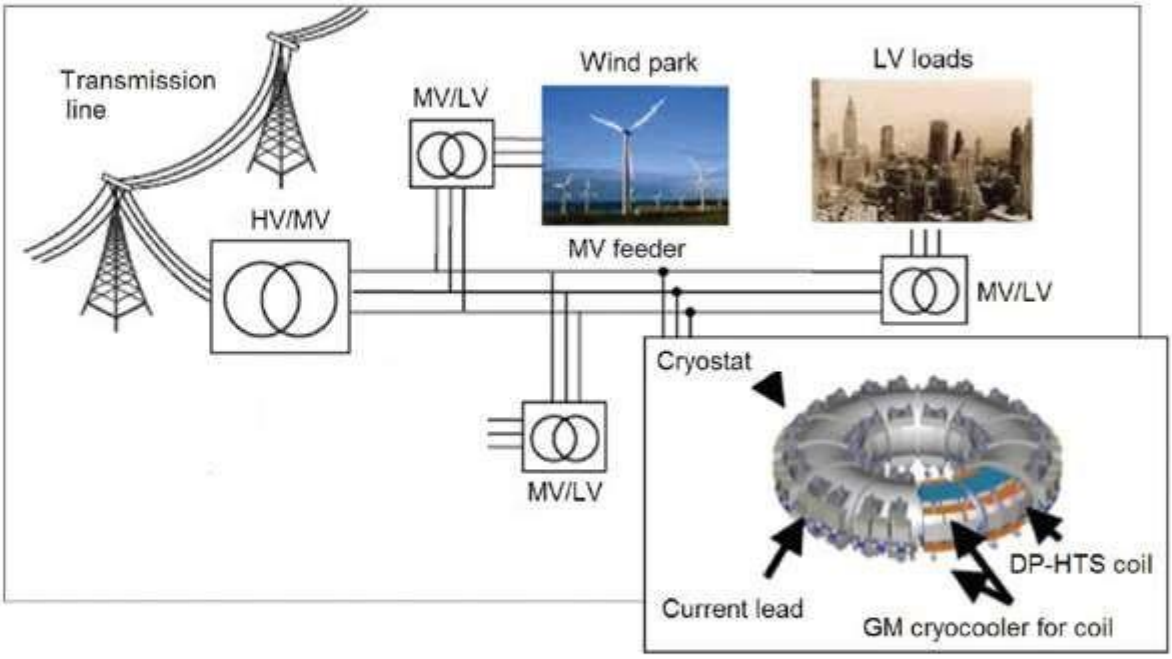


Figure 2.14: **Superconducting Magnetic Energy Storage System**

2.8.2.6 Hydrogen Energy Storage (HES)

HES is one of the most undeveloped technologies (Luimnigh & Connolly, 2009). It is not a single device but the process is divided into three portions:

- Hydrogen Production
- Hydrogen Storage
- Hydrogen conversion to energy

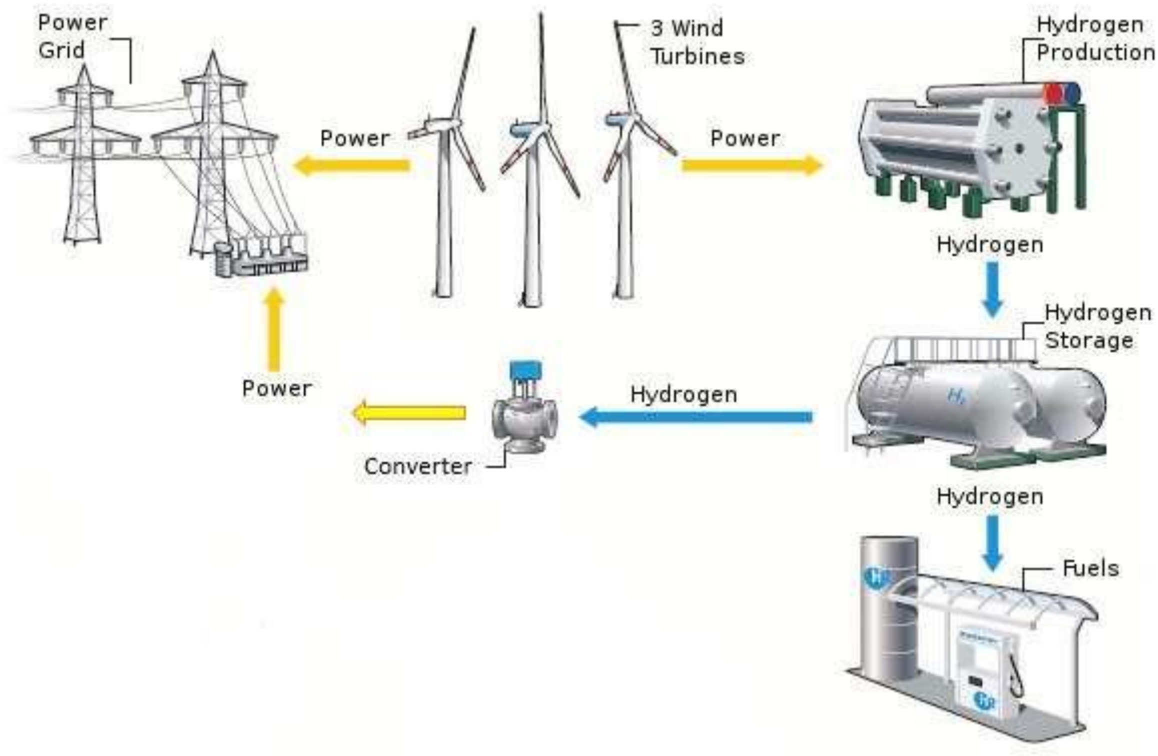


Figure 2.15: **Hydrogen Energy Storage System (Gonzalez et al., 2004)**

Hydrogen can be produces by extraction of fossil fuels, reacting steam with methane and by electrolysis. Producing hydrogen from electrolysis is the most cheaper option compared to other solutions. Production from fossil fuels is four times costly compared to using the fuel itself (Luimnigh & Connolly, 2009). Producing hydrogen from reaction of steam with methane creates pollution. During the process of electrolysis, hydrogen is generated from water and oxygen is dispursed into atmosphere. Latest developments improved the effectiveness of hydrogen production to 85%. Hydrogen storage can be done by compressing hydrogen, by liquefying it or by metal hydride (Ollscoil Luimnigh, David Connolly, University of Limerick "An investigation into the energy storage technologies available, for the integration of alternative generation techniques", 2009).The most commonly used option is the compression of hydrogen (65- 75% efficiency). Hydrogen Storage can also be done in liquefied form by pressuring and cooling hydrogen. But keeping the hydrogen liquid demands a lot of energy because of the very low temperature that has to be continuously maintained. To produce energy from hydrogen there are two methods to be used, such as,Fuel Cell (FC) and Internal Combustion Engine (ICE). Round trip efficiency is between 30 to 50%.

Fuel cell is comparatively new technology and do not have any moving parts, no emissions, are not heavy and they are reliable. Hydrogen has a higher energy density per weight but lower per volume compared to a gasoline. These characteristics provide a lot of potential in the future and also with the renewable applications but technology needs to be more advanced.

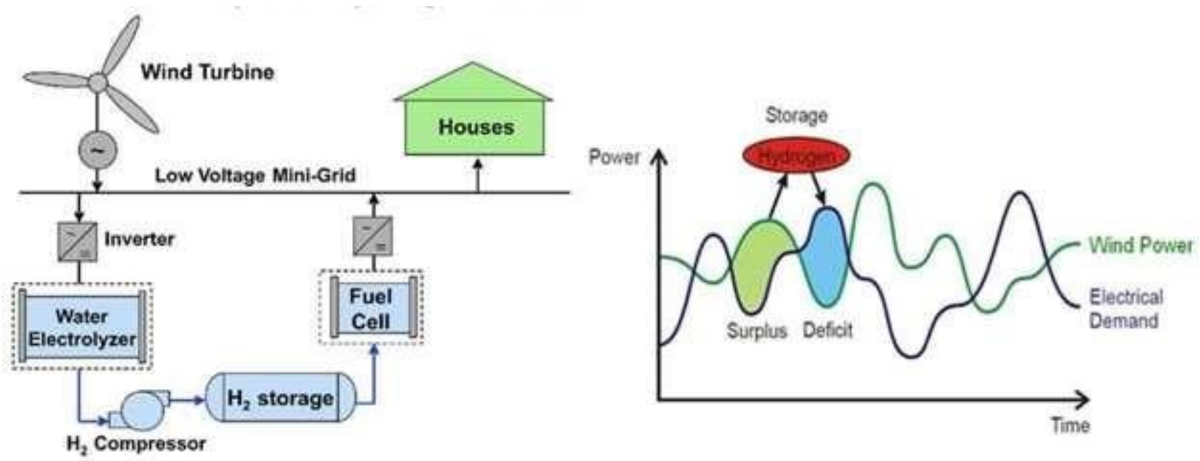


Figure 2.16: **Wind Hydrogen System (Gonzalez et al., 2004)**

Hydrogen is an energy carrier, not an energy source.

An Electrolyser, Hydrogen Storage and a Fuel Cell are used to store the excess electricity generated by wind turbines and produce electricity from hydrogen when needed.

2.8.2.7 Batteries and Ultracapacitors

Electrochemical cells/batteries together with capacitors are electrical energy storage devices. Capacitors store electrical energy electrostatically by separating opposite charges. Electrochemical cells/batteries create charges on electrodes by redox reactions (ECOFYS, 2014).

Batteries and ultracapacitors can be considered complimentary energy storage systems for smart grid storage. Ultracapacitors can be used for power quality application for short term disruption smoothing while batteries could do the long term storage.

The technology and characteristics of some of the most used battery types and ultracapacitors are explained in the following subchapters.

2.8.2.7.1 Battery Energy Storage (BES)

Batteries are electrochemical energy storage devices. BES transforms chemical energy in electrical energy through chemical reactions and vice versa (Cho et al., 2015). The batteries have been categorised in conventional batteries, high temperature batteries and flow batteries.

Conventional batteiries consists of an anode and cathode electrodes in a sealed cell seperated by an electrode. When the electrolyte is ionised the charging takes place and during discharge the energy is recovered with an oxidation reduction reaction. The most common conventional batteries are lead acid, nickel-cadmium and lithiumion (ECOFYS, 2014). Conventional batteries are providing energy storage for rewable energy and decentralised grids. Main application areas for conventional batteries are photovoltaic energy, solar and wind hybrid systems, telecommunication networks, energy power back-up and generator starting application, UPS and emergency and security systems.

The difference between flow batteries and conventional and high temperature ones is that in flow batteries the electrolyte is stored in an external tank. The electrolyte is pumped from the tank to the cell stack and vice versa during charging and discharging. This construction method increases is costly and increases the maintenance. There are also efficiency losses associated with the pumps and other ancillary equipment needed (ECOFYS, 2014). Flow batteries have been categorised in hybrid and redox batteries (ECOFYS, 2014).

The battery cell of hybrid flow batteries consists of one electrode and one fuel cell electrode and it uses an electro-active component placed as a solid layer. The size of the electrode determines the energy capacity (ECOFYS, 2014).

Redox flow batteries use electro-active components dissolved in the electrolyte. This type of battery is a reversible fuel cell. The most common redox flow batteries are vanadium batteries and zinc bromine (ECOFYS, 2014).

Flow batteries are suitable for large storage systems due to their scalability and flexibility in system design. System power and capacity can be varied independently by adjusting cell stack size and electrolyte volumes. Their cost decreases as the energy storage capacity increases making them suitable for very high energy applications. Flow batteries can be coupled with renewable energy sources such as wind. Very high capacities of flow battery could be integrated in medium voltage grids for energy/power supply in weak nodes (Alliance, 2012).

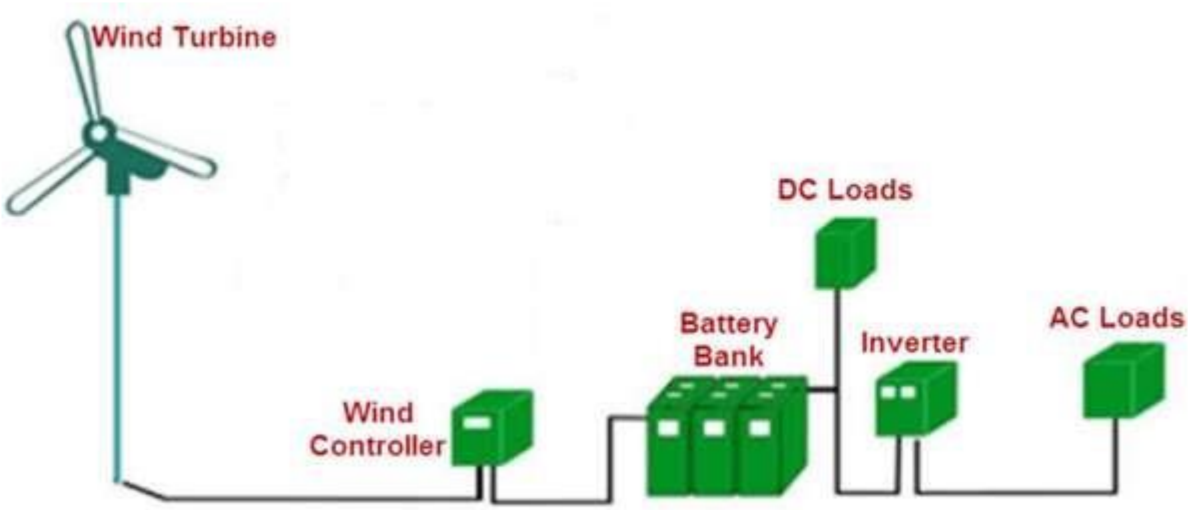


Figure 2.17: **Battery Energy Storage System (Luo et al., 2015)**

2.8.2.7.2 Lead Acid Battery Energy Storage (LAES)

LAES is the most mature and the most commonly used battery storage technology presently (Luimnigh & Connolly, 2009). There are two types of lead acid batteries distinguished, such as, Valve Regulated Lead Acid (VRLA) and Flooded Lead Acid (FLA). FLA batteries are built from two lead plates which are immersed in a mixture of sulphuric acid and water. In case of VRLA batteries, the operating principle is the same, but they are sealed with a pressure regulating valve which stops venting of the hydrogen and removes the air from the cell. VRLA are having higher initial cost and shorter lifetime, but they have an advantage compared to FLA in lesser weight, volumes and lower maintenance cost.

LAES may be considered as a support of wind power. There is an existing stationary application of LAES in the world rated in MW for power system applications, but LAES normally lose compared to other batteries so far as wind power integration, mostly because of low depth discharge, smaller power density, extreme sensitivity to temperature changes and life cycle capability. Furthermore, depth cycles are reducing the lifespan of LA batteries. Presently effort is applied in research of LA batteries that capable of being charged in minutes (Luimnigh & Connolly, 2009). It is rather not likely that this technology will be playing a significant part in the future as a large scale storage device, mainly because of a very limited number of cycles. And also, an interesting solution appears to be ultra-battery as well, which is LAES with integrated super-capacitor in one unit cell established by CSIRO. Ultra battery can offer high power discharge and charge with a long and low cost life (A Study by the DOE Energy Storage Systems Program. Sandia report, 2001).

2.8.2.7.3 Nickel Cadmium Battery Energy Storage (NCES)

Nickel Cadmium is an advance solution similar to LA batteries (Gonzalez et al., 2004). NCES comprises of positive electrode (nickel hydroxide) and negative electrode (metallic cadmium). Electrodes are divided by nylon divider and aqueous potassium hydroxide is the electrolyte. During discharging process nickel oxyhydroxide reacts with water and creates nickel hydroxide and hydroxide ion. Cadmium hydroxide is produced at the negative electrode. The process is reversed during charging process of the battery.

NiCd batteries can function in wider temperature range compared to LA. NiCd are able to achieve much more cycles when they are operated with depth of discharge.

It is rather not likely to utilize this technology for WPP purposes (Luimnigh & Connolly, 2009). There is a possibility of total prohibition of NiCd batteries by European Commission (A Study by the DOE Energy Storage Systems Program, 2001). Life time of NiCd batteries can be reduced significantly for a deep cycles. However, this technology suffers from memory effect. Furthermore, the other problem with this technology is the environmental impact. Cadmium is a toxic heavy metal and there are challenges in relation to its disposal.

2.8.2.7.4 Lithium Ion Battery Energy Storage (LIES)

LIES technology was first obtainable commercially in 1990 (A Study by the DOE Energy Storage Systems Program, 2001). This technology has the lithiated metal oxide cathode while the anode is graphic carbon with layer structure (Electrical Energy Storage Technology Review, 2012). Furthermore, the electrolyte is a lithium salt in organic solvent. In this case, lithium migrates from anode to cathode during discharging. And vice versa occurs during charging. The weight of LIES is about one and a half more compared to NCES of comparable capacity and a volume is 40 to 50% lesser than NCES (Luimnigh & Connolly, 2009).

This Technology becomes a serious player in large scale applications and can be sized in MW. LIES appear to be relevant for WPP. The characteristics and features of this technology are small weight, high efficiency, high cell voltage and power density. LIES can be made into a wide range of shapes and sizes. Moreover, this technology does not have a memory effect. Other characteristics are small self discharge (at approximately 0.1% per month) and lengthy lifespan for deep cycles. It is likely that LIES performance will be significantly improved because of a lot of research is done especially in respect to electric cars.

2.8.2.7.5 Sodium Sulphur Battery Energy Storage (NaSES)

Sodium Sulphur batteries was available commercially in the year 2000. The cell is normally constructed in a tall cylindrical configuration. Positive electrode and negative electrode contains molten sulphur and molten sodium, respectively (Luimnigh & Connolly, 2009). Electrolyte in this case is solid β-alumina. Therefore, sodium ions pass through electrolyte and combines at positive electrode with sulphur, creating sodium polysulfide, during discharging of the battery. During charge process reaction is vice-versa. NaSES battery can be categorized to group of high temperature batteries. The Cell has to operate in temperature range of between 320 to 340°C, because sulphur has to be kept in liquid form. The batteries will suffer serious damage if they are to be cooled down when not fully charged. For that reason, a diesel genset is often implemented together with a NaSES installation to mitigate in cases of power outage.

This technology can become a serious player in large scale applications and can be sized in MW. NaSES appears to be more suitable for WPP. There are presently existing operational applications of NaSES with WPP.

The feature and characteristic of NaSES is high energy density, three times higher compared to LAES (Luimnigh & Connolly, 2009). NaSES have a capacity to survive much more cycles compared to LA batteries. The cost of Sodium Sulphur batteries is now relatively high, however it is considered to drop with a mass production because these batteries are constructed from inexpensive, abundant and recyclable materials (Luimnigh & Connolly, 2009). Presently, there is only one manufacturer of NaSES batteries and it’s called NGK Insulators in Japan.

2.8.2.7.6 Sodium Nickel Chloride Battery Energy Storage (ZEBRA)

Sodium Nickel Chloride battery belong to the family of high temperature batteries and are popularly known as ZEBRA. Positive electrode and Negative electrode consists of nickel chloride and liquid sodium (like NaS), respectively. Moreover β-alumina electrolyte is used, but in conjunction with a second liquid electrolyte (sodium chloroaluminate) which is used to permit fast transport of sodium ions from the solid nickel chloride electrode to and from ceramic electrolyte (Sudoworth, 2001). The exceptional performance of a cell is realized on a temperature range of between 250 to 350 °C.

In integration of renewables, ZEBRA batteries are able to play a role in the future. However currently, ZEBRA batteries aim specifically in e-mobility. This technology is featured by high energy density, five times more compared to LA. They are also resistant to short circuits. Furthermore compared to NaS, ZEBRA batteries are able to survive certain overcharge and discharge and have better safety features and a higher cell voltage (A Study by the DOE Energy Storage Systems Program, 2001).

2.8.2.7.7 Flow Battery Energy Storage (FBES)

The following are the distinguished 3 types of flow batteries, such as, Zinc Bromine (ZnBr), Vanadium Redox (VR) and Polysulphide Bromide (PSB). The operating principle of Flow batteries is different from that of conventional batteries. By means of reversible reaction between two electrolytes, energy is stored as a potential chemical energy. It is stored in the electrolyte solutions. This makes the power and energy capacity disengaged. The power capacity is determined by the size of the cell stack, while the energy capacity is determined by volume of electrolyte (A Study by the DOE Energy Storage Systems Program, 2001). The 2 electrolytes charged are pumped by the cell stack. The chemical reaction occurs in the cell stack (Luimnigh & Connolly, 2009).

Operation of Polysulphide Bromide (PSB) is comparable to VR. The characteristic of this technology is the very fast reaction time. PSB batteries can be used for frequency response and voltage control. The disadvantage is the fact that small quantities of bromine, hydrogen and sodium sulphate produce what imposes some maintenance (Luimnigh & Connolly, 2009). In case of Zinc Bromine (ZB) technology, operating principle is different to previously mentioned VR and PSB batteries, however it contains the same components. The electrolytes of zinc and bromine ions flow to the cell stack, during the charging process. The electrolytes are divided by a microporous membrane. The difference is that electrodes in a ZnBr flow battery act as substrates to the reaction. As the reaction occurs, zinc is electroplated on the negative electrode and bromine is evolved at the positive electrode (similar to conventional battery operation).

This technology can be sized in MW and therefore it can become a critical player in large scale applications. FBES appears to be appropriate for WPP. There are already existing operational applications of VR with WPP.

2.9 Overview of Connected Sites to Eskom Networks

In South Africa, there are currently no large scale wind farms operational, though a number of them are in planning and construction phases.

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.

2.9.1 Dassiesklip Wind Farm

Nine wind turbines have been installed in South Africa in the Dassiesklip wind farm, located approximately 5km west of Caledon in the Western Cape Province. A wind farm utilised a leased area of approximately 602 hectares. Each of the nine wind turbines has a capacity of 3MW, with a total installed capacity of 27MW for the whole wind farm. This project connects to an existing 66kV line. One of the aspects that give direction for the wind energy research is power quality and local effect of wind turbines on grid. Hence the study on power quality impact of wind turbines on distribution networks.

Two 66kV feeder bays were constructed which interconnects directly into the existing 66kV Houhoek–Caledon line. A Sinovel SL3000/113 turbine was installed, which is a 3MW turbine, 100m hub height and 113m rotor diameter.

Figure 2.18 shows an aerial view of the wind farm.

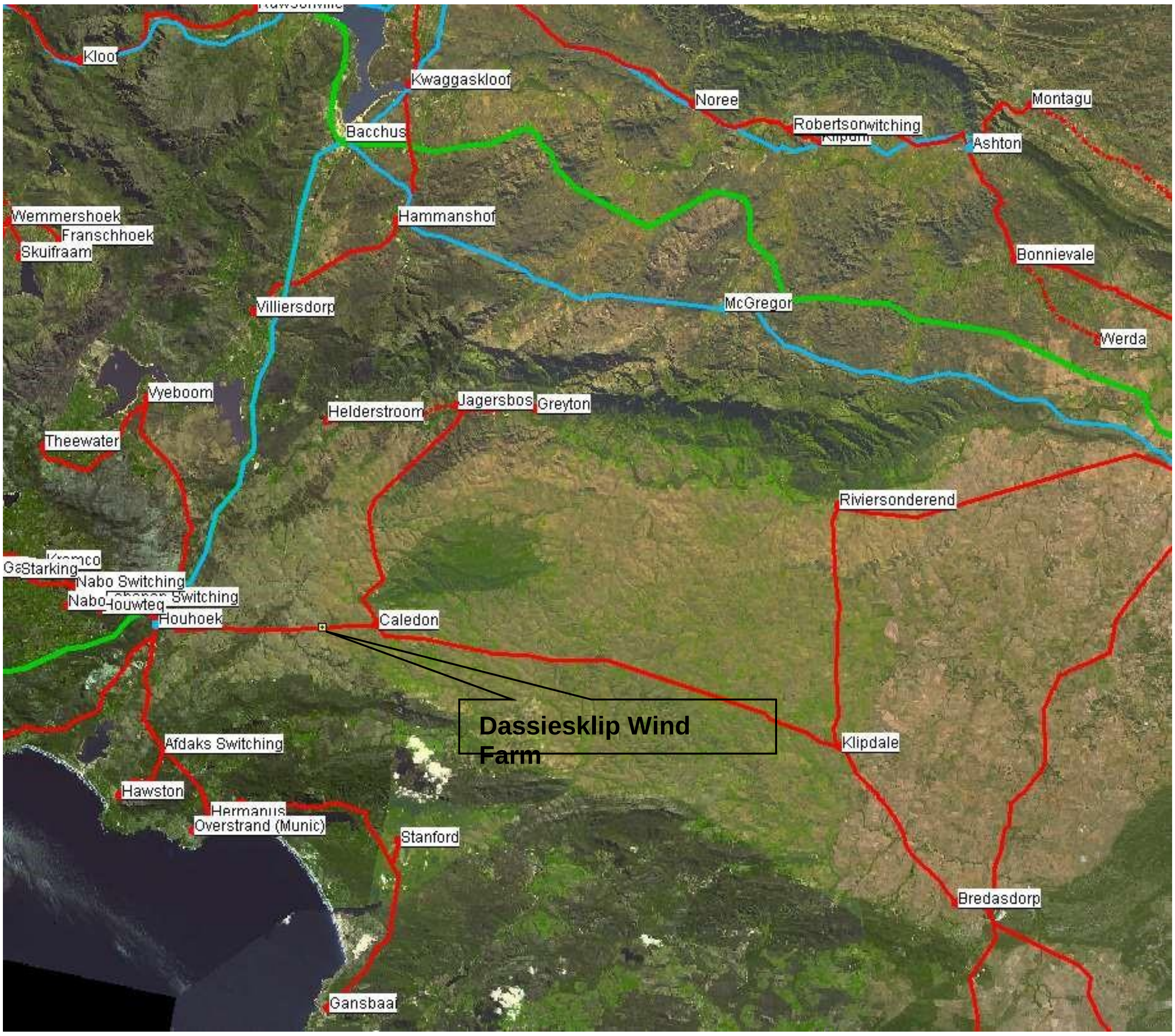


Figure 2.18: **The electrical connection of Dassiesklip Wind farm**

2.9.2 The Connection of Dassiesklip to Eskom Grid

The Dassiesklip Wind Farm is exporting a full 27MW to the Eskom grid at wind speeds over 46km per hour. At a daily average consumption of 20kWh per house, the wind farm will be able to supply more than 11000 homes. A large house will consume up to 48kWh per day in which case the wind farm will supply in the order of 5000 houses.

Figure 2.19 shows a single line diagram for Dassiesklip Wind Farm and how data loggers are installed for power quality studies.

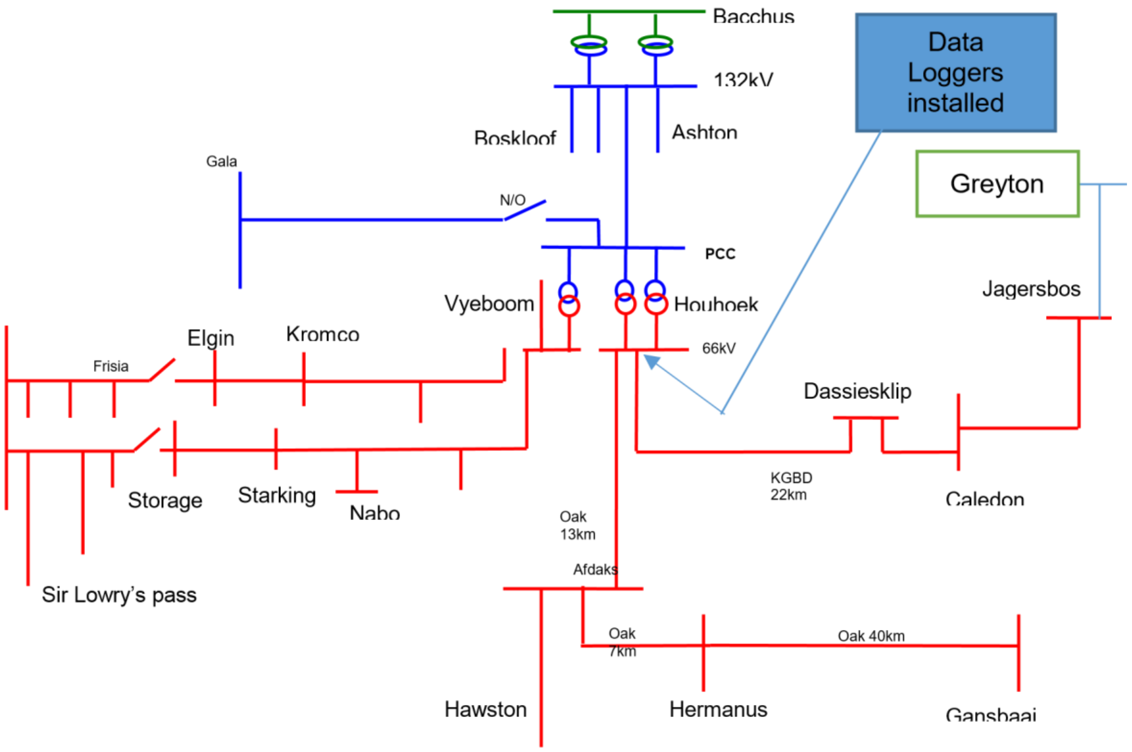


Figure 2.19: Single Line Diagram for Dassiesklip Wind Farm

2.9.3 Distribution Networks in South Africa

Distribution networks are generally designed to accept bulk power supply from transmission lines and distribute it to different customers. The usual power flow would therefore be from higher to lower voltages. 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. South African distribution networks are determined to function at a voltage of up to 132kV.

The majority of South African distribution networks in rural areas are constrained by voltage related challenges rather than capacity or waveform quality (Larsson, 1996). 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 quite high impedance of the distribution lines. The distribution nature of network load indicates that rural distribution feeders are long, and have relatively small HV/MV transformer capacities (from 750kVA) (Larsson, 1996).

Variations in both active and reactive power have an impact on steady state voltage variations. 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.

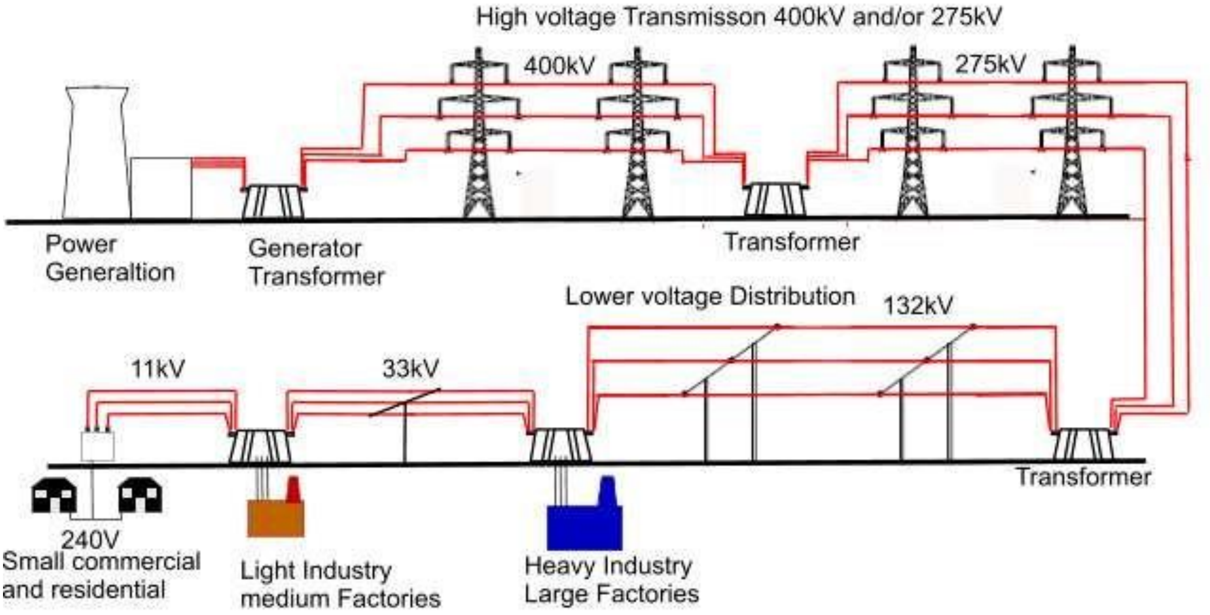


Figure 2.20: **Distribution Networks**

2.10 Theoretical aspects of Power Quality

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.

2.10.1 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" (Arsenal Research, 2004). 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" (Arsenal Research, 2004). NRS 048-2 (NRS 048-2. South African standards on quality of supply, n.d.) 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."

Flawless power quality means that the voltage is constant and sinusoidal, having a constant amplitude and frequency (Larsson, 2002). 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 defined in terms of voltage disturbances, frequency and interruptions.

Figure 2.21 shows the classification of power quality (Larsson, 2002). However, not all the characteristics of power quality are presented in the chart. A lot of attention will however be directed 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.

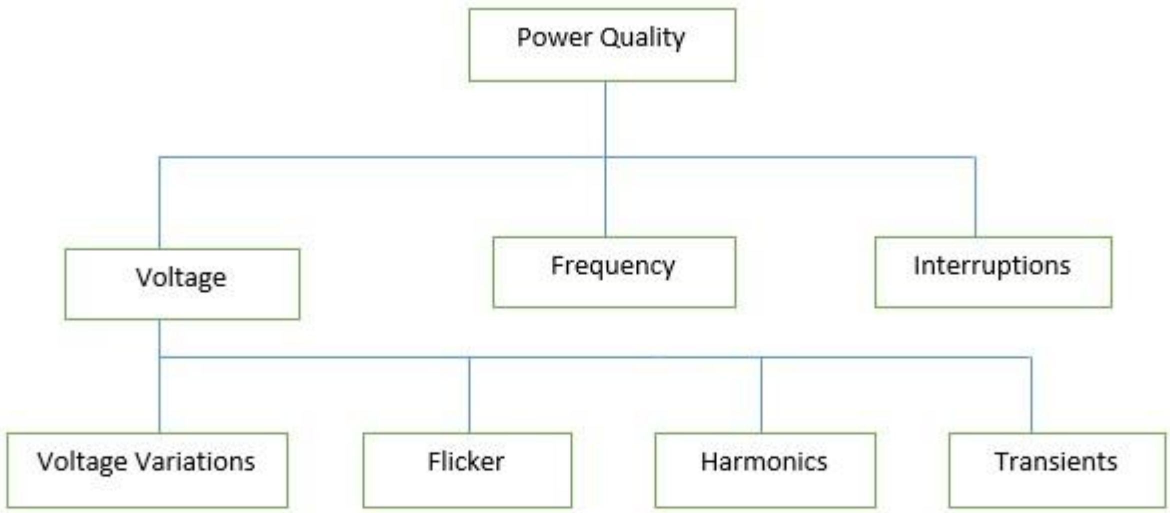


Figure 2.21: **Classification of different power quality phenomena (Larsson, 2002)**

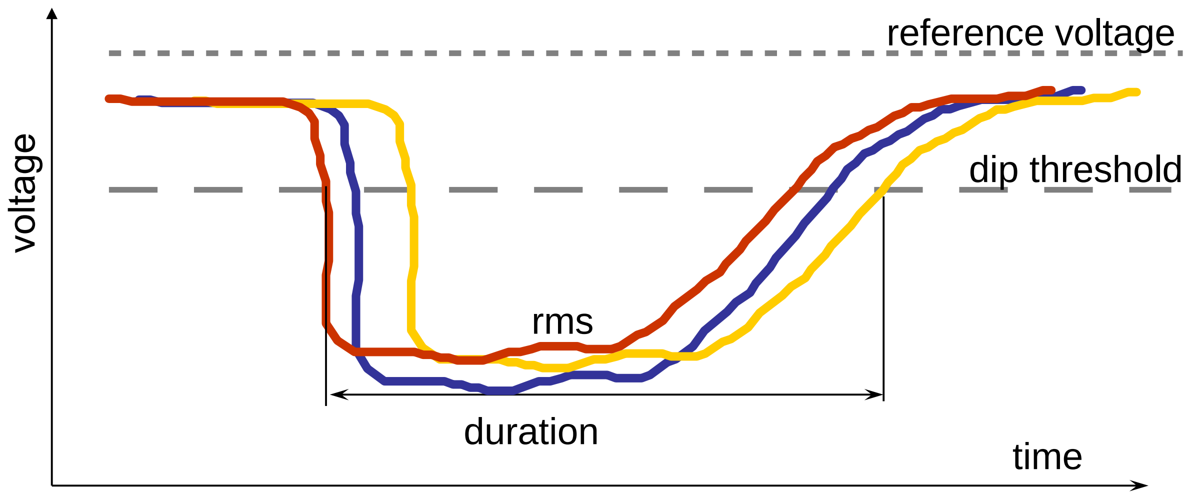
2.10.2 The Characteristics of Power Quality

The following are the measurable quantities or occurrences of power quality (Jenkins et al., 2000), (Nguyen, 2009).

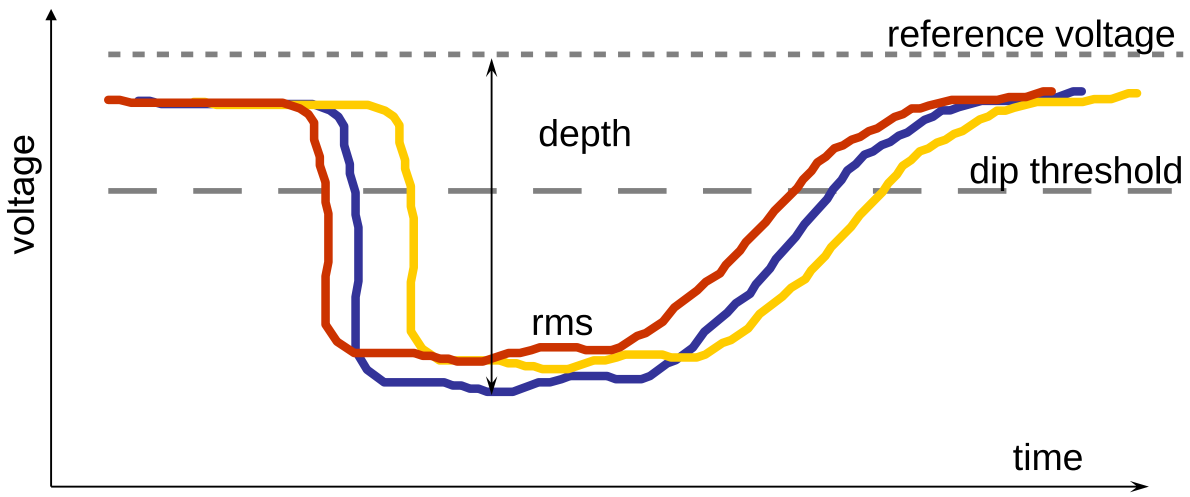
2.10.2.1 Voltage Dip

Voltage Dip is the decrease in the RMS voltage, for a period of between 20ms to 3s (NRS 048-2. South African standards on quality of supply, n.d.). The duration of a voltage dip is the period measured from the moment the RMS voltage drops below 0.9 per unit of declared voltage to when the voltage increases above 0.9 per unit of declared voltage (NRS 048-2. South African standards on quality of supply, n.d.). The cause of voltage dip is usually faults on the transmission or distribution networks, increased load demand and transitional events such as starting of big motors. It is said that start-up of a wind turbine can cause sudden voltage drop (Tande, 2002).

However, voltage dips are not a restriction for further expansion of wind farms.



(a)



(b)

Figure 2.22: Dip Parameters (a) Duration and (b) Depth caption

2.10.2.2 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 (Larsson, 2002). This voltage transient can disturb sensitive equipment connected to the same grid (Larsson, 2002). 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.

$$f = \frac{1}{2\pi}\sqrt{\frac{1}{LC}}$$

Equation 2.7

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.

2.10.2.3 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., l00Hz, 150Hz, 200Hz, 250Hz, etc. Variable speed wind turbines are said to generate harmonics while fixed speed wind turbines are not expected to cause significant harmonics.

2.10.2.4 Voltage Flicker

Voltage flicker is the visual impact 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.

2.10.2.5 Frequency Deviation

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

2.10.3 Power Quality of Wind Turbines

Grid-connected wind turbines are said to have effect on the power quality of the grid where they are connected (Larsson, 2002). 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 (Larsson, 2002). 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 (Larsson, 1996), 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 *61400-2] (IEC 61400-21, 2001).*

Fixed speed wind turbines are said to have a higher flicker emission as they have a high flicker coefficient C(ψ_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.

2.10.3.1 Steady State Voltage Fluctuations

Operation of wind turbines may have effect on the steady state voltage of the connected network (Larsson, 1996). Steady state voltage fluctuations are measured using the following two-node system.

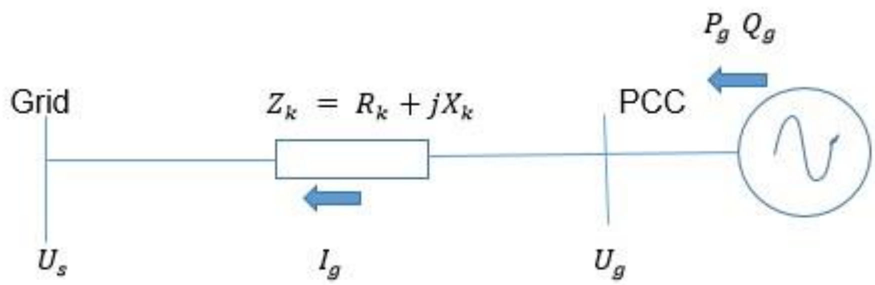


Figure 2.23: **Simple Impedance Model (Jenkins, 2000)**

This system illustrates a wind farm connected to a network with equivalent short circuit impedance Z_k. Us 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:

$$I_g = \frac{S_g}{U_g}$$

Equation 2.8

Where:

$S_g = P_g - jQ_g$

Equation 2.9

Therefore, the voltage difference ΔV is given by the following equation:

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

Equation 2.10

From the equation above, it can be seen that voltage difference is interrelated 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 produced 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.

The voltage level impact on the grid with fixed speed wind turbines depends largely on the grid X/R ratio and a smaller extent on the induction generator characteristics (Thiringer et al., 2004).

Tower shadow effects are largely the cause of voltage fluctuations. Power output is reduced every time the blade passes a tower. For a three bladed wind turbine, the power losses will appear three times per revolution of the turbine.

2.10.3.2 Flicker Emission or Dynamic Voltage Fluctuations

Power variations in the region of 0.01 to 10 Hz are created by the turbulence in the wind together with the wind turbine itself (Thiringer et al., 2004). However, the possibility to reduce the dynamic voltage fluctuations is provided by the use of power electronic converters in wind turbine system (Thiringer et al., 2004). 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 (Chen et al., n.d.). Rapid variations in power output of a wind turbine, such as generator switching and capacitor switching can also cause in fluctuations 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.

2.10.3.3 What is Flicker?

Larsson (Larsson, 2002) 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.

Flicker-meter is used to measure flicker. The method is based on measurements of variations in the voltage magnitude. The flicker-meter architecture is divided into two parts, each performing one of the following tasks: (IEC 61400-21, 2001), (Tande, 2002)

- Simulation of the reaction of the lamp-eye-brain chain, which is weighted by two different filters, one relates to the reaction of a 60W lamp and the other to the reaction of the human eye and brain to disparities in the luminance of the light bulb.
- Online arithmetic breakdown of the flicker signal and demonstration 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 [20]. 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 applied 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.
- Voltage and Current measurements. Instantaneous current measurements are used to compute voltage, which is applied as an input to flicker algorithm.

2.11 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.

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.

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.

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.

Nine wind turbines have been installed in the Dassiesklip wind farm, located approximately 5km west of Caledon in the Western Cape Province. A wind farm utilised a leased area of approximately 602 hectares. Each of the nine wind turbines has a capacity of 3MW, with a total installed capacity of 27MW for the whole wind farm. This project connects to an existing 66kV line. One of the aspects that give direction for the wind energy research is power quality and local effect of wind turbines on grid. Hence the study on power quality impact of wind turbines on distribution networks.

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.

CHAPTER THREE

MODELLING WIND TURBINES USING DIGSILENT

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 Dassiesklip wind farm as will be discussed in chapter 4. The DigSilent studies were done to show the effects of changing power production of an induction generator, as a distributed generator, connected to a 66kV network. An induction generator was chosen as the studied wind turbine use this type of a generator.

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 (Chiradeja, 2005).

A complete structure of a wind turbine model is composed of an electric model, mechanical model, aerodynamic model and the wind model. The electrical model is composed of built-in models, like the grid, transformers, capacitors and generators. 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 4.

The network below is modelled with DigSilent.

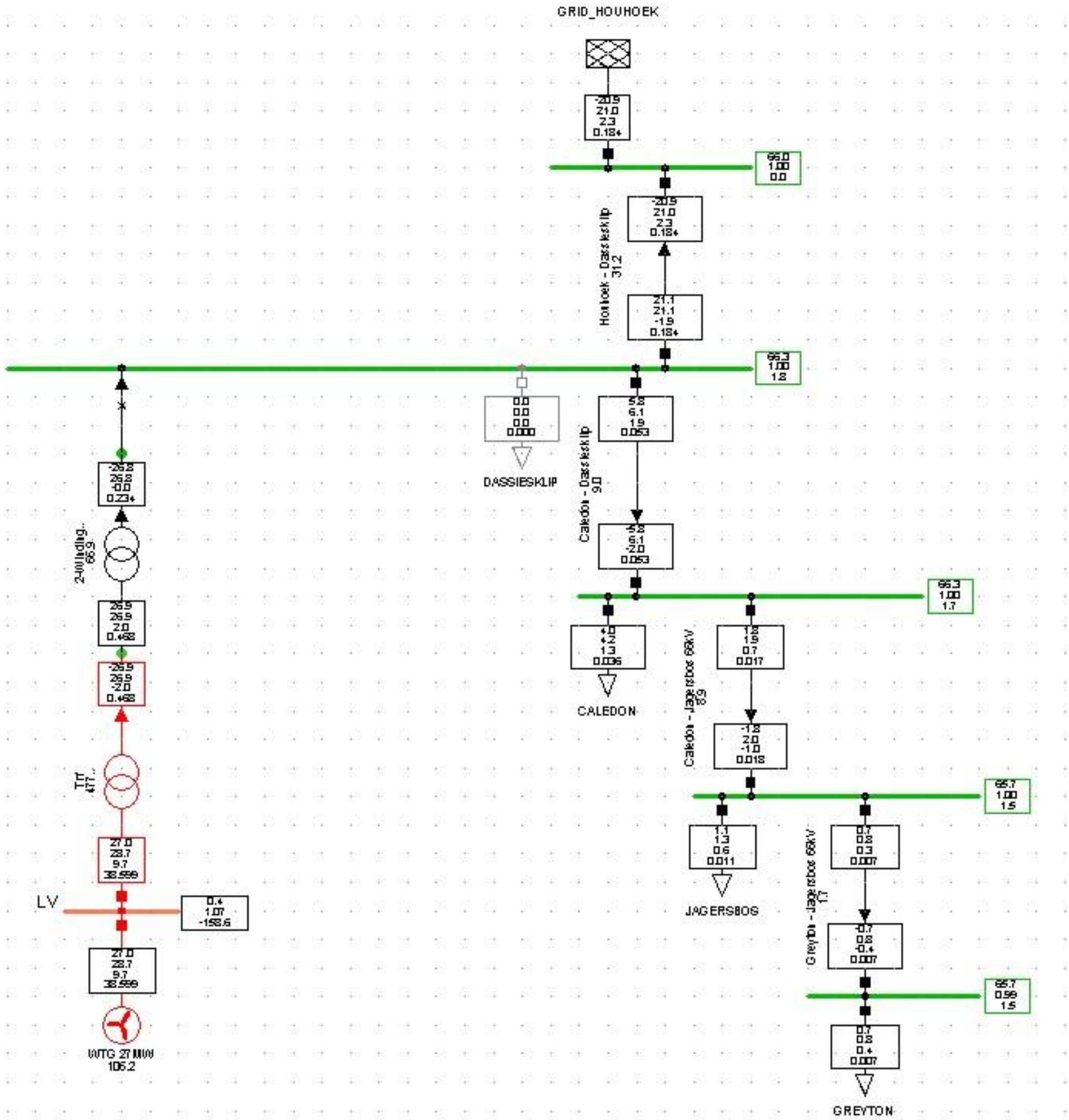


Figure 3.1: **DigSilent Modelled Network**

3.1 Load Flow Calculations

3.1.1 Steady State Operation

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.

It has been seen that at low X/R ratios, i.e. X/R ratio ≤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 generated by the generator result to a voltage surge because of the grid resistance. The reactive power consumed by the generator result to a voltage drop over the grid reactance. For an X/R ratio of about 2, these voltages have approximately the same size.

3.1.2 Voltage Variation Calculations

According to Larsson, (Larsson, 1996), two different occurrences take place between the grid and the turbine. These occurrences are stationary variation in the power production and power fluctuations. Both of these occurrences have an impact on voltage variations. Stationary voltage variations are the results of the power generated by the turbine, while power variations that occur at a frequency between 1 to 2 Hz are largely triggered by the tower shadow (Larsson, 1996).

3.1.3 Power Fluctuations due to Wind Variations

Power from the wind turbines is determined by the equation:

$$P = {}^{1}/{2}\ C_p\ \rho\ V^3$$

Equation 3.1

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 loss will appear 3 times. This is known as a 3p frequency. The occurrence of power fluctuation is equivalent to the total number of blades multiplied by the rotational speed.

The effect of tower shadow and wind gradient to power variations 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.

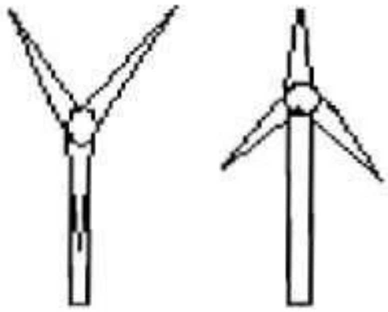


Figure 3.2: **Tower Shadow Effect**

High power fluctuations occur at high wind speed, as wind speed fluctuation increase with wind speed (Larsson, 1996).

3.2 Flicker during Continuous Operation

Flicker is a measure of dynamic voltage fluctuations. It is because of the fact that people are being annoyed by the flickering of the light bulb. The level of flicker is classified by the 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 shortterm flicker is calculated using a reference grid.

Flicker was monitored in Houhoek 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 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 4. Firstly, the measurements were taken at the point of common connection (PCC), which is where the other loads such as farmers are connected. The low flicker values at the PCC could mean that the grid is not experiencing high voltage fluctuations especially at frequencies between 1 -10Hz.

3.3 Digsilent Simulation and Results

An equivalent network is used to represent the Eskom network impedance at the Point of Connection (POC), (the Dassiesklip 66 kV busbar), to evaluate power quality performance of the Wind Energy Facility (WEF). These values were given as the present maximum and future maximum fault levels and not the current maximum and minimum fault levels. The following information was provided:

Table 3.1: **Existing Fault Level - Dassiesklip 66 kV Busbar**

3-Phase fault level [kA]	Angle [deg]	Positive Sequence R [pu]	Positive Sequence X [pu]
2.8	-78.2	0.0694	0.3326

Table 3.2: **Future Fault Level - Dassiesklip 66 k' Busbar**

3-Phase fault level [kA]	Angle [deg]	Positive Sequence R [pu]	Positive Sequence X [pu]
5.1	-79.7	0.0339	0.1862

As the existing fault level is a worst case scenario, a fault level of 2.8 kA and a R/X ratio of 0.209 is assumed for the equivalent network. The impact of only the Dassiesklip WEF on the power network is studied.

3.4 High Frequency Currents and Voltages

When considering the impact on the power quality for the Dassiesklip WEF project, it is necessary to consider the impact that the Sinovel SL3000/113 machines will have on the power network.

Sinovel provided the measured power quality test result for the Sinovel SL3000/113 machines. The harmonic currents (I_h) produced per harmonic order for the Sinovel SL3000/113 machine are given in Table 3.3.

Table 3.3: **Harmonic currents**

Order	Harmonic current (% of I_n)
2	0.42
3	0.35
4	0.23
5	1.25
6	0.17
7	0.65
8	0.0
9	0.0
10	0.0
11	0.15
12	0.0
13	0.21
14	0.0
15	0.0
16	0.0
17	0.16

It is necessary to determine the compliance of the Sinovel machines in the Dassiesklip WEF with the national power quality limits.

The "ESKOM DISTRIBUTION CONNECTION AND USE OF SYSTEM AGREEMENT WITH GENERATORS" states the following:

"THE CUSTOMER'S OBLIGATION"

The CUSTOMER shall so connect to the ESKOM system as not to interfere with an efficient and economical supply to other customers of ESKOM, and shall ensure that any voltage distortions caused by the Facility shall not at any time exceed the limits specified in Sections C.1.1, C.1.2, C.1.3, C.1.4 and C.1.5.

HARMONIC VOLTAGE EMISSION LEVELS

The CUSTOMER shall ensure that the harmonic voltage emission levels from the Facility at the Point of Common Coupling shall at all times not exceed the limits set out in the following Table 3.4:

Table 3.4: **Harmonic Voltage Emission Limits**

Harmonic Order	Voltage (%)
2	0.2
3	1.2
4	0.1
5	0.5
7	0.5
9	0.2
11	0.6
13	0.6
23	0.4
25	0.3

The CUSTOMER shall ensure that all other harmonic voltage emission levels at all other frequencies not specified in Table 3.4 caused by the CUSTOMER at the Point of Common Coupling shall be less than 30 % of the individual voltage harmonic limits as specified in NRS 048-2 (In the case where no limit is provided in the NRS 048-2, 30 % will be taken from the NRS048-4 planning limits)."

The power quality and harmonic limits in the Republic of South Africa Electricity Supply Industry are governed by a set of standards, known as NRS048. These standards set the compatibility limits, maximum limits and suggested planning limits for various power quality phenomena. These standards also define exactly how the measurements are to be taken.

3.5 Dassiesklip Wind Farm Harmonic performance – Existing fault level

3.5.1 Total Harmonic Distortion

To evaluate the WEF harmonic performance, a harmonic study is performed. The Total Harmonic Distortion (THD) is obtained at the POC and the 22 kV Dassiesklip busbar. The results are shown in Table 3.5.

Table 3.5: **THD of the wind farm**

Name	Total Harmonic Distortion (%)	Voltage Level (kV)	NRS 048 Limit	NRS 048 Planning Limit
POC 66kV	2.16	66	4	3
Dassiesklip 22kV	3.93	22	8	6.5

The NRS048 limit shown in Table 8 is the total harmonic distortion at the POC. The THD limit is not exceeded at the POC.

3.5.2 Individual Harmonic Distortion

The individual harmonic distortion for the complete wind farm is also obtained at the POC. A bar graph is obtained. This is shown in Figure 3.3.

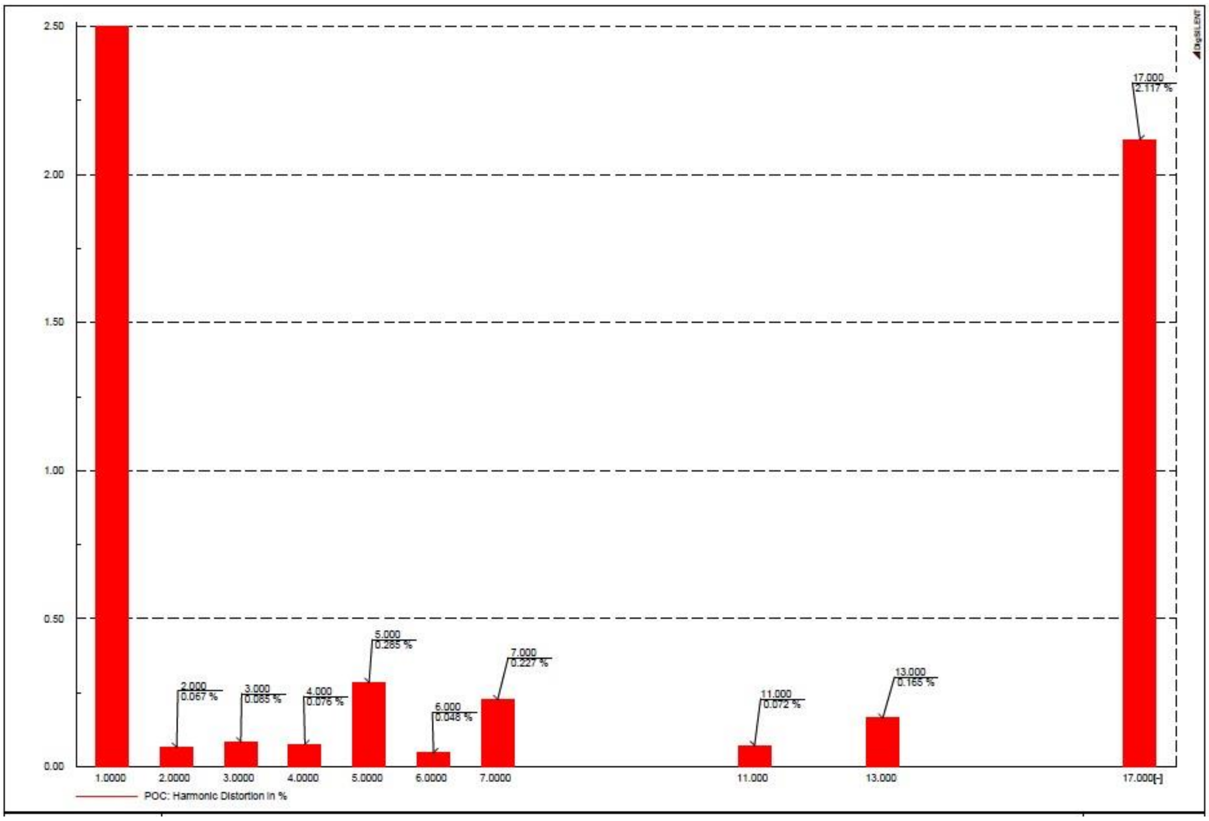


Figure 3.3: **Individual harmonic distortion at the POC – existing fault level**

The “ESKOM DISTRIBUTION CONNECTION AND USE OF SYSTEM AGREEMENT WITH GENERATORS” distributes, or allocates, proportionally the amount of Harmonic Distortion (HD) that the specific WEF can contribute. This quantity is known as the apportionment limit.

The “ESKOM DISTRIBUTION CONNECTION AND USE OF SYSTEM AGREEMENT WITH GENERATORS” does not include harmonic limits for all the frequencies identified by NRS048. Where no limit is given in “ESKOM DISTRIBUTION CONNECTION AND USE OF SYSTEM AGREEMENT WITH GENERATORS”, this agreement suggests that 30 % of the NRS 048 Planning limit be used.

A violation is based on the lower of the NRS 048 planning limit and the limit specified by the “ESKOM DISTRIBUTION CONNECTION AND USE OF SYSTEM AGREEMENT WITH GENERATORS”.

Table 3.6: Individual harmonic distortion per harmonic order at the POC

Harmonic Order	Dassiesklip 66kV Harmonic Distortion (%)	NRS 048 Limit (%)	NRS 048 planning Limit (%)	Distribution Connection Agreement Limit (%)
1	100			
2	0.067	Not specified	1.5	0.2
3	0.085	2.5	2	1.2
4	0.076	Not specified	1	0.1
5	0.285	3	2	0.5
6	0.048	Not specified	0.5	0.2
7	0.227	2.5	2	0.5
9	0.00	Not specified	2	0.2
11	0.072	1.7	1.5	0.6
12	0.00	Not specified	0.2	0.06
13	0.165	1.7	1.5	0.6
15	0.00	Not Specified	0.3	0.1
17	2.117	1.2	1	0.4
19	0.00	1.2	1	0.4
23	0.00	0.8	0.7	0.4
25	0.00	0.8	0.7	0.3

From Table 3.6, all of the calculated harmonics are within the limit required by the “ESKOM DISTRIBUTION CONNECTION AND USE OF SYSTEM AGREEMENT WITH GENERATORS” and the NRS 048, except for the 17th harmonic.

3.5.3 Possible measures to make the Wind Farm comply with the Harmonic Limits

Inspection of the 17th harmonic voltage and current indicates that the impedance measured at the POC is very much greater than at other harmonics which suggests that a parallel resonance exists between the inductive impedance of the 66/22 kV transformer in series with the Eskom network and the Wind Farm's cable capacitance. This is confirmed by means of an impedance scan performed at the POC. The detailed results are shown in Figure 3.4.

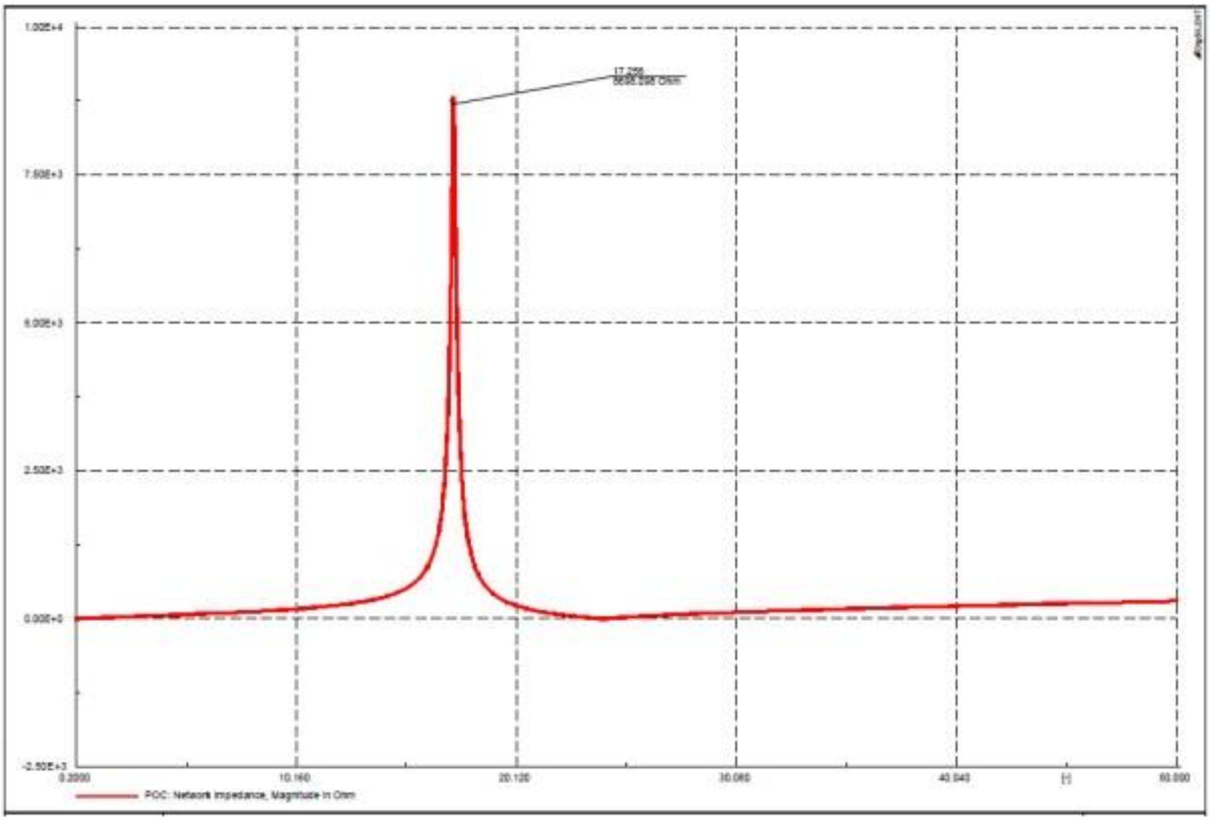


Figure 3.4: **Impedance scan – existing fault level**

Three ways of overcoming the problem were investigated; namely:

- Reducing the Dassiesklip 66/22 kV transformer impedance
- Installing a shunt capacitor on the 22 kV busbar at Dassiesklip ▪ Installing a 17th harmonic filter

3.5.3.1 Reduction of Transformer Impedance or Shunt Capacitor

The graph below shows the harmonic distortion for the harmonics up to the 17th for

- the "as is" network,
- the network with the transformer impedance reduced from 7,7 % to 4 %, and
- the network with shunt capacitors of 100, 200, 300 and 400 kvar, respectively.

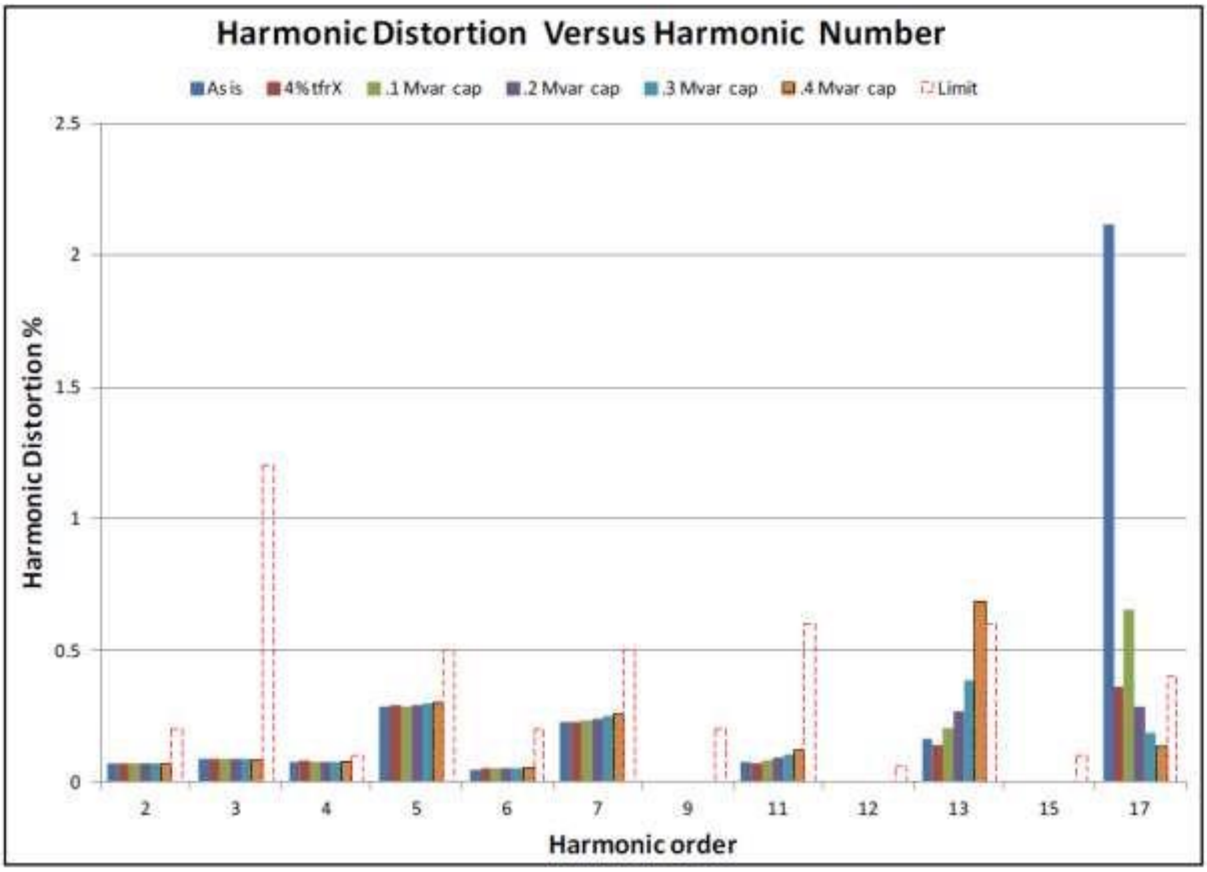


Figure 3.5: **Harmonic distortion for different mitigation solutions**

Figure 3.5 shows a problem at the 17th harmonic with the "as is" network. Reducing the transformer impedance moves the resonance point to a higher frequency. The details are shown in Figure 3.6:

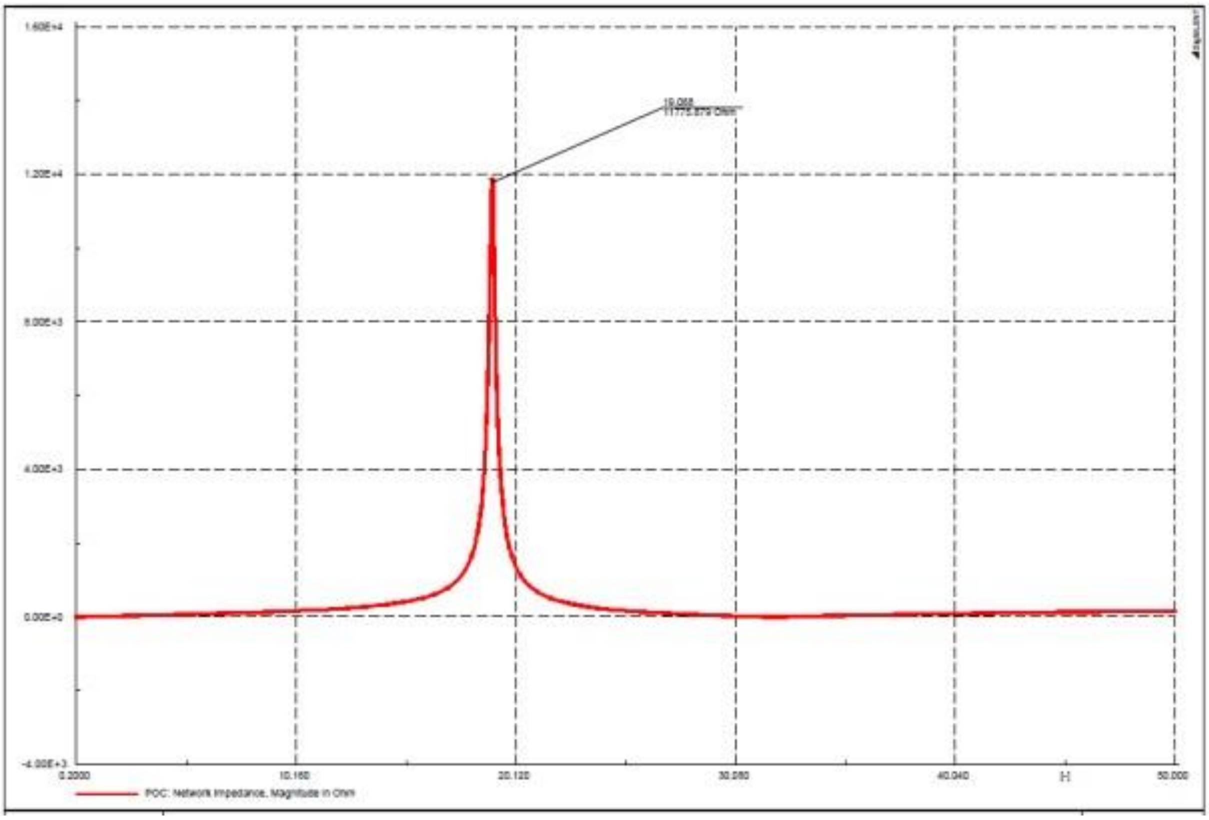


Figure 3.6: **Impedance scan – reduced transformer impedance**

The addition of shunt capacitors (0.2 Mvar cap) to lower frequencies is shown in Figure 3.7:

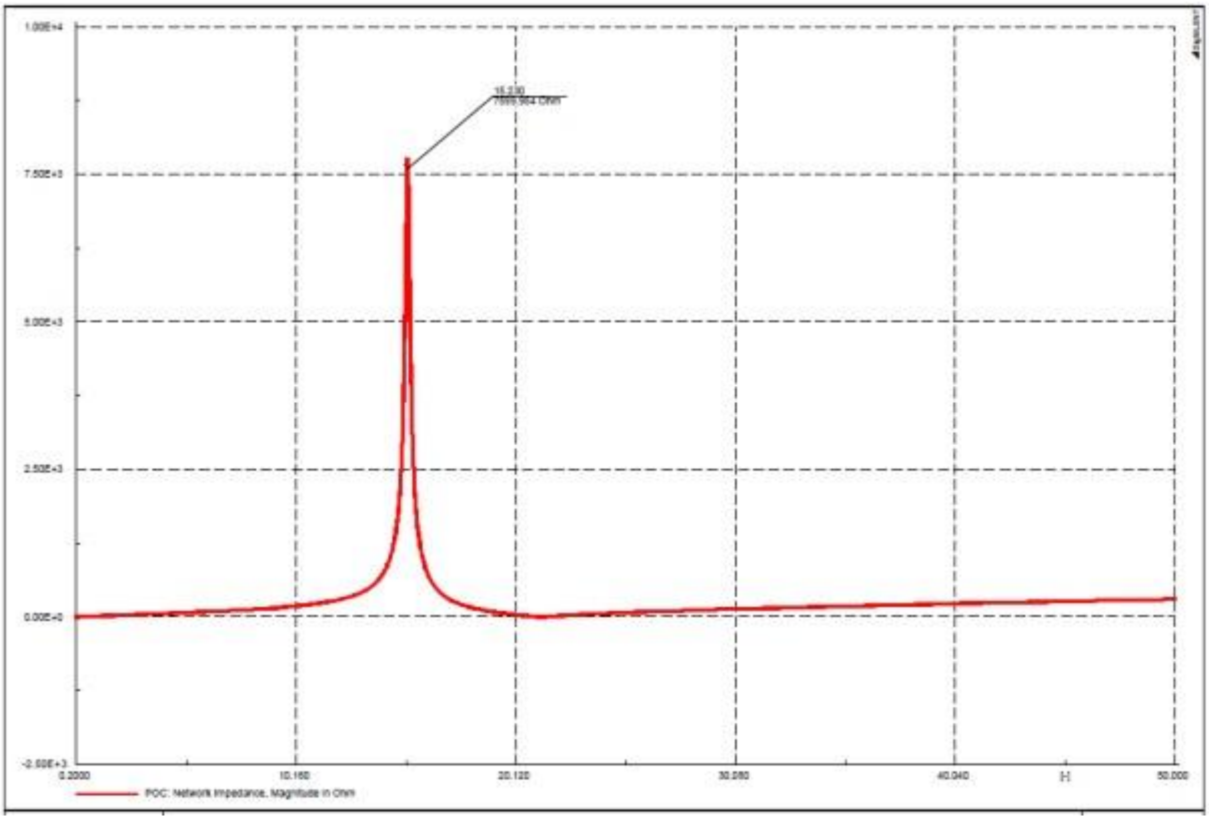


Figure 3.7: **Impedance scan – 0.2 Mvar capacitor**

The higher frequency is not an issue as no harmonic currents are given beyond the 17th and it is assumed the Wind Farm does not generate harmonics above the 17th harmonic. The reduced transformer impedance option is thus technically acceptable. The graphic in Figure 3.5 shows that two of the shunt capacitor options (0,2 and 0,3 Mvar) are also acceptable as the harmonic distortion is within limits, up to and including the 17th harmonic.

The most acceptable shunt capacitor appears to be the 0,2 Mvar as the harmonic distortion is the least up to the 17th harmonic. The shunt capacitor lowers the resonant frequency as can be seen in Table 3.7.

Table 3.7: **Resonant frequency the shunt capacitors considered**

Shunt Capacitor	Resonant Frequency (HZ)
100kvar	16.1
200kvar	15.2
300kvar	14.4
400kvar	13.8

Wind Farm harmonic current injection is given at the 13th and 17th harmonic but nothing in between, making the 15th harmonic a suitable resonant frequency, being equally distant from the 13th and the 17th harmonics. This confirms the earlier finding that a shunt capacitor of 0,2 Mvar is the optimum size.

Table 3.8 presents the total harmonic distortion with the 0,2 Mvar shunt capacitor.

Table 3.8: **THD at Dassiesklip**

Name	Total Harmonic Distortion (%)	Voltage Level (kV)	NRS 048 Limit (%)	NRS 048 Planning Limit
POC 66kV	0.57	66	4	3
Dassiesklip 22kV	1.03	22	8	6.5

The THD is comfortably within the required NRS 048 planning limit with, or without, the shunt capacitor.

3.5.3.2 Shunt Filter

The simplest way to ensure that the WEF meets the harmonic requirements is to install a filter tuned to the 17th harmonic. Installing a filter will result in two resonant frequencies, instead of one; one frequency is greater than the 17th harmonic and the other below. Illustrating results are given in Figure 3.8:

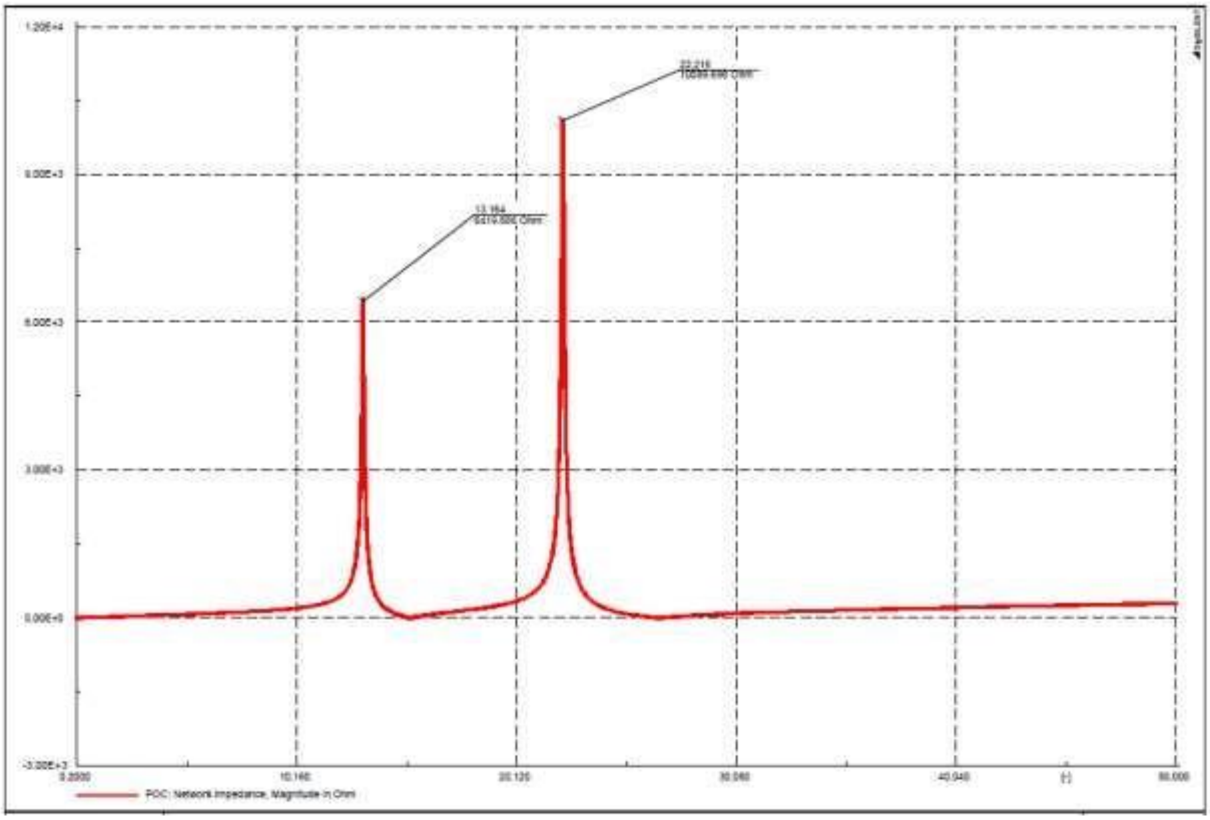


Figure 3.8: **Impedance scan – 17th harmonic filter installed**

As the filter causes a resonance below the 17th harmonic, no advantage is seen over a 0,2 Mvar shunt capacitor. The fact that it will require more components than the shunt capacitor is another disadvantage and the filter is not considered further.

3.5.4 Recommendation

It is recommended that a 0,2 Mvar shunt capacitor be installed on the 22 kV busbar at Dassiesklip to meet harmonic requirements while the Eskom network fault current is 2,8 kA on the Dassiesklip 66 kV busbar.

On account of the real Eskom network having a possible 15th harmonic current source, it is further recommended that Eskom be informed of a possible 15th harmonic violation due to harmonics in their network.

3.6 Dassiesklip Wind Farm Harmonic performance – Future fault level

3.6.1 Wind Farm including a 0,2 Mvar Shunt Capacitor

3.6.1.1 Total Harmonic Distortion

A harmonic study was performed to evaluate the WEF harmonic performance with the future fault level and a 0,2 Mvar shunt capacitor. The Total Harmonic Distortion (THD) was obtained at the POC and the Dassiesklip 22 kV busbar. The results are shown in Table 3.9:

Table 3.9: **THD at Dassiesklip - Future fault level and 0,2 Mvar capacitor**

Name	Total Harmonic Distortion (%)	Voltage (kV)	NRS 048 Limit (%)	NRS 048 Planning Limit (%)
POC 66kV	3.17	66	4	3
Dassiesklip 22kV	7.86	22	8	6.5

The NRS048 limit shown in Table 3.9 is the total harmonic distortion at the POC. The THD obtained from the simulation study shows violations of the NRS 048 planning limit at both the 66 kV and 22 kV busbars.

3.6.1.2 Individual Harmonic Distortion

This section of the report investigates the effect of the 0,2 Mvar shunt capacitor at a future fault level of 5,1 kA.

Table 3.10: **THD at Dassiesklip - Future fault level and 0,2 Mvar capacitor**

Harmonic Order	Dassiesklip 66kV Harmonic Distortion (%)	NRS 048 Limit (%)	NRS 048 planning Limit (%)	Distribution Connection Agreement Limit (%)
1	100			
2	0.039	Not specified	1.5	0.2
3	0.049	2.5	2	1.2
4	0.044	Not specified	1	0.1
5	0.165	3	2	0.5
6	0.028	Not specified	0.5	0.2
7	0.132	2.5	2	0.5
9	0.00	Not specified	2	0.2
11	0.043	1.7	1.5	0.6
12	0.00	Not specified	0.2	0.06
13	0.099	1.7	1.5	0.6
15	0.00	Not Specified	0.3	0.1
17	3.155	1.2	1	0.4
19	0.00	1.2	1	0.4
23	0.00	0.8	0.7	0.4
25	0.00	0.8	0.7	0.3

From Table 3.10, it can be seen that the harmonic limit at the 17th harmonic is exceeded if the 0,2 Mvar shunt capacitor is in service. Switching out the shunt capacitor ensures that the harmonic limits are well within those specified for all harmonics for which information was given.

3.6.2 Wind Farm and no Shunt Capacitor

3.6.2.1 Total Harmonic Distortion

A harmonic study is performed to evaluate the Wind Farm harmonic performance with the future fault level. The Total Harmonic Distortion (THD) is obtained at each busbar throughout the Wind Farm, including the POC. The results are shown in Table 3.11.

Table 3.11: **THD at Dassiesklip - Future fault level no 0,2 Mvar capacitor**

Name	Total Harmonic Distortion (%)	Voltage (kV)	NRS 048 Limit (%)	NRS 048 Planning Limit (%)
POC 66kV	0.297	66	4	3
Dassiesklip 22kV	0.737	22	8	6.5

The NRS048 limit shown in Table 3.11 is the total harmonic distortion at the POC. The THD obtained from the simulation study is well below the required limit.

3.6.2.2 Individual Harmonic Distortion

The individual harmonic distortion for the complete wind farm is also obtained at the POC with the future fault level and no capacitor. A bar graph is obtained. This is shown in Figure 3.9.

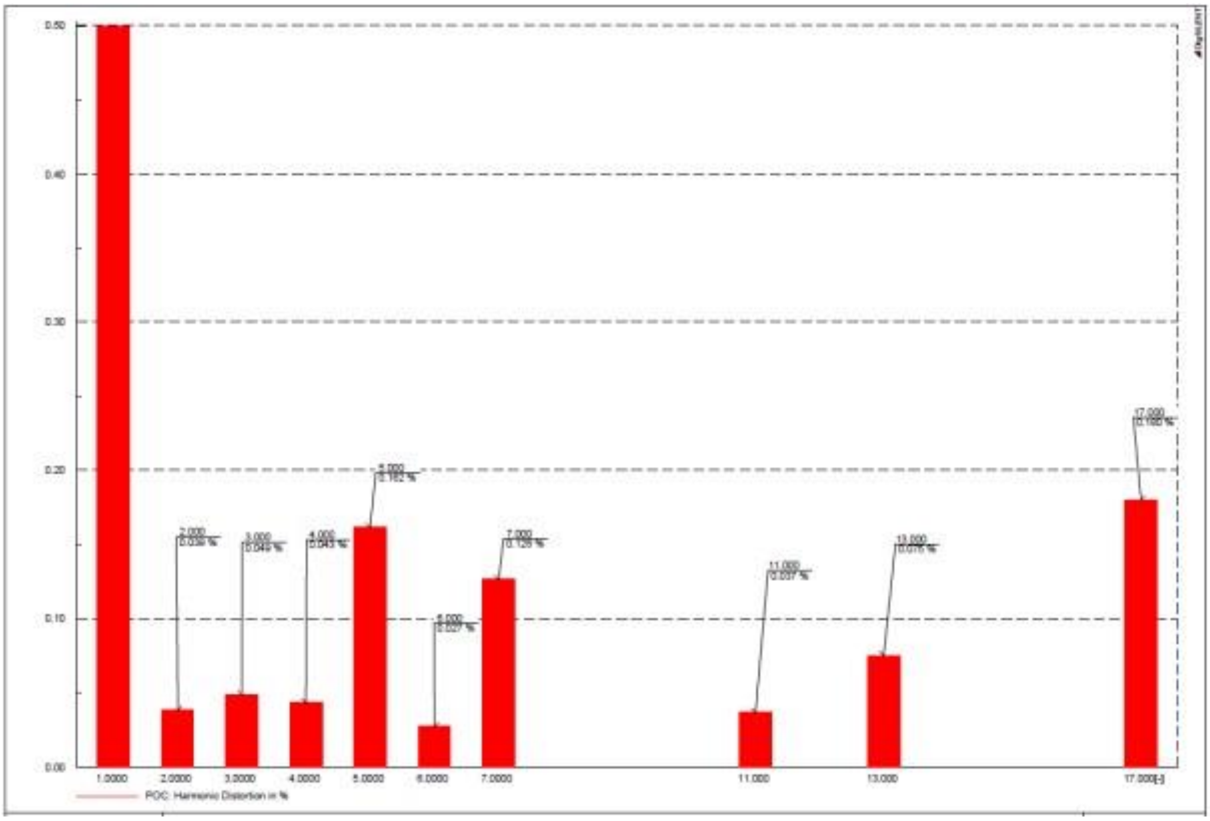


Figure 3.9: **Individual harmonic distortion at the POC – future fault level**

From Figure 3.9, it can be seen that the fundamental is 100 % and all other harmonic distortion voltages are below 0.5 %.

The results are compared to the limits, both planning and apportionment, in Table 3.12.

Table 3.12: **Individual harmonic distortion per harmonic order at the POC**

Harmonic Order	Dassiesklip 66kV Harmonic Distortion (%)	NRS 048 Limit (%)	NRS 048 planning Limit (%)	Distribution Connection Agreement Limit (%)
2	0.039	Not specified	1.5	0.2
3	0.049	2.5	2	1.2
4	0.043	Not specified	1	0.1
5	0.162	3	2	0.5
6	0.027	Not specified	0.5	0.2
7	0.126	2.5	2	0.5
9	0.00	Not specified	2	0.2
11	0.037	1.7	1.5	0.6
12	0.00	Not specified	0.2	0.06
13	0.075	1.7	1.5	0.6
15	0.00	Not Specified	0.3	0.1
17	0.180	1.2	1	0.4
19	0.00	1.2	1	0.4
23	0.00	0.8	0.7	0.4
25	0.00	0.8	0.7	0.3

All harmonics are well below the lesser of the "ESKOM DISTRIBUTION CONNECTION AND USE-OF-SYSTEM AGREEMENT WITH GENERATORS" and Wind Farm should easily conform to the harmonic requirements at the 66 kV busbar at Dassiesklip Substation with the future fault levels without any intervention such as shunt capacitors, filters or transformer impedance reduction.

3.7 Voltage Fluctuations - Flicker

Compatibility levels for both long term and short term flicker for connection to an electrical network are stipulated in NRS 048-4. NRS 048-4 states the following:

The indicative values given in table 3.13 should be used as planning levels for shortterm voltage flicker severity (P_{st}) and long-term flicker severity (P_{lt}) unless the licensee has established its own planning levels for a particular system.

Table 3.13: **THD at Dassiesklip**

Supply	P_{st}	P_{lt}
HV/EHV	0.8	0.6
MV	0.9	0.7

The “ESKOM DISTRIBUTION CONNECTION AND USE OF SYSTEM AGREEMENT WITH GENERATORS” also states flicker limits which are more stringent than those given in the NRS 048-4. The following is an extract from the “ESKOM DISTRIBUTION CONNECTION AND USE Of SYSTEM AGREEMENT WITH GENERATORS”:

The CUSTOMER shall ensure that the contribution to voltage flicker by the Facility at the Point of Common Coupling for the range of reference fault levels shall at all times be less than the following amounts:

- In the case of short-term voltage flicker, 0.4
- In the case of long-term voltage flicker, 0.3

The flicker data supplied by Sinovel is used to calculate the flicker. This is shown in Table 3.14 and Table 3.15.

Table 3.14: **Sinovel Flicker Values**

	Network impedance phase angle (°)			
	30	**50**	**70**	**85**
Average wind speed (m/s)	Flicker coefficient			
6	5.32	4.90	4.66	4.74
7.5	5.34	4.92	4.68	4.77
8.5	5.34.	4.94	4.68	4.77
10	5.34	4.94	4.68	4.78

Table 3.15: **Sinovel switching operation**

Case of switching operation	**Start up at rated wind speed**			
Max. Number of switching operations, N_{10}	1			
Max. Number of switching operations, N_{120}	12			
Grid impedance angle (°)	30	50	70	85
Flicker step factor	0.15	0.12	0.11	0.11
Voltage change factor	1.02	0.79	0.48	0.23

With this data included in the model, the following results are obtained:

Table 3.16: **Flicker Results**

Flicker	Simulation results			Connection standard limit	NRS 048-4 Limit
	Existing Fault level	Existing fault Level and 0,2 Mvar Shunt Capacitor	Future Fault Level		
P_{st}	0.126	0.1725	0.073	0.4	0.9
P_{lt}	0.126	0.1725	0.073	0.3	0.7

From Table 3.16, it can be seen that the Wind Farm will conform to the flicker requirements. Flicker results calculated with the future fault level indicate a substantial reduction compared with those from the existing fault levels. In both instances, the results are well within the required limits.

3.8 Unbalanced Currents and Voltages

The layout of the Wind Farm has been designed such that the cables connecting the wind turbines introduce no negative phase sequence voltages and currents. This has been achieved by the use of three single phase cables arranged in trefoil.

The output of the wind turbines comprises three voltages and currents, balanced in both magnitude and phase. This ensures that no negative sequence voltages and currents are generated by the wind turbines.

Thus, the output of the Wind Farm, with wind turbines generating balanced voltages and currents and a cable network with balanced impedances and admittances, is substantially balanced.

3.9 Voltage Change due to a Switching Event – existing fault level

Different interpretations exist of SECTION 9 - (6) of the “GRID CONNECTION CODE FOR RENEWABLE POWER PLANTS (RPPs) CONNECTED TO THE ELECTRICITY TRANSMISSION SYSTEM (TS) OR THE DISTRIBUTION SYSTEM (DS) IN SOUTH AFRICA” (hereafter referred to as “SAGCRPP”) which states, “The maximum allowable voltage change at the POC after a switching operation by the RPP (e.g. of a compensation device) shall not be greater than 2%”. The Grid Code Advisory Committee’s understanding of this section implies that the voltage change on switching out the complete Wind Farm must be analysed.

The other interpretation is based on the Relative Voltage Change as defined in IEC 61400-21.

The results of both interpretations are included below.

3.9.1 Existing fault level- Wind Farm Disconnection

The voltage change studied was the complete switching out of the Wind Farm. Table 3.17 shows the voltage change that can be expected when the Wind Farm, at full active power output and at different power factors, is switched off. It fails to meet the requirement at all operating points.

Table 3.17: **Rapid voltage changes – existing fault level**

Operating point	Voltage before switching event (p.u.)	Voltage after switching event(p.u.)	% voltage change
Unity power factor	1.046	1.025	2.1%
0,975 pf, exporting reactive power	1.076	1.025	5.1%
0,975 pf, importing reactive power	1.014	1.025	1.1%

3.9.2 Future fault level - Wind Farm Disconnection

The voltage change studied was the complete switching out of the Wind Farm. Table 3.18 shows the voltage change that can be expected with the WEF at full active power output and at different power factors with the future fault level incorporated. It just fails to meet the requirement at 0,95 power factor, leading.

Table 3.18: **Rapid voltage changes– future fault level**

Operating point	Voltage before switching event (p.u.)	Voltage after switching event(p.u.)	% voltage change
Unity power factor	1.044	1.036	0.8%
0,975 pf, exporting reactive power	1.058	1.036	2.2%
0,975 pf, importing reactive power	1.040	1.036	0.4%

3.9.3 Voltage Change Factor

From Table 3.15, the voltage change factors are as given below for the different network impedance angles ($\boldsymbol{tan^{-1X/R}}$)

Table 3.19: **Voltage change factor**

Case of switching operation	Start up at rated wind speed			
Grid impedance angle (°)	30	50	70	85
Voltage change factor	1.02	0.79	0.48	0.23

Based on these Voltage Change Factors, the following voltage changes are calculated.

Table 3.20: **Relative Voltage Change**

Network Angle	30	50	70	85
Voltage change factor	1.02	0.79	0.48	0.23
Relative voltage change	0.58	0.45	0.27	0.13

The equivalent grid impedance angle is 79,7° and so the voltage change is well within the required 2 %.

3.10 Summary

In this chapter, a study was conducted on DigSilent software to measure power quality of wind turbines. A case study was done, where a wind turbine is represented by an induction generator to simulate steady state voltage variations. 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 ≤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 Dassiesklip Wind Farm.

Power fluctuations are as a result of tower shadow effects as well as wind speed variations. Flicker was monitored in Houhoek 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 Dassiesklip wind turbines.

CHAPTER FOUR

POWER QUALITY STUDIES ON DASSIESKLIP WIND FARM

This chapter presents the results obtained from Dassiesklip 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 Houhoek 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, taking measurements from each wind turbine would require nine 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.

4.1 Voltage Unbalance of Houhoek 66kV Compliance with NRS048-2:2003

Voltage Unbalance measurements are assessed according to NRS048-2:2003 section 4.2.4. These 7 day sliding assessments are compared to the specified compatibility and limit criterium values day by day. Compliance over the whole time period is presented as percentages of the time that each criterium is met.

Table 4.1: Voltage Unbalance Weekly Assessment

First Day	Last Day	Max	95% Highest	Ave	95% Lowest	Min
2017/06/01	2017/06/07	0.8%	0.7%	0.5%	0.4%	0.3%

Compatibility Criterion	Compliance Level	Worst Assessment	Compliance	Non Compliance
95% Highest	2.0%	0.7%	100%	0.0%

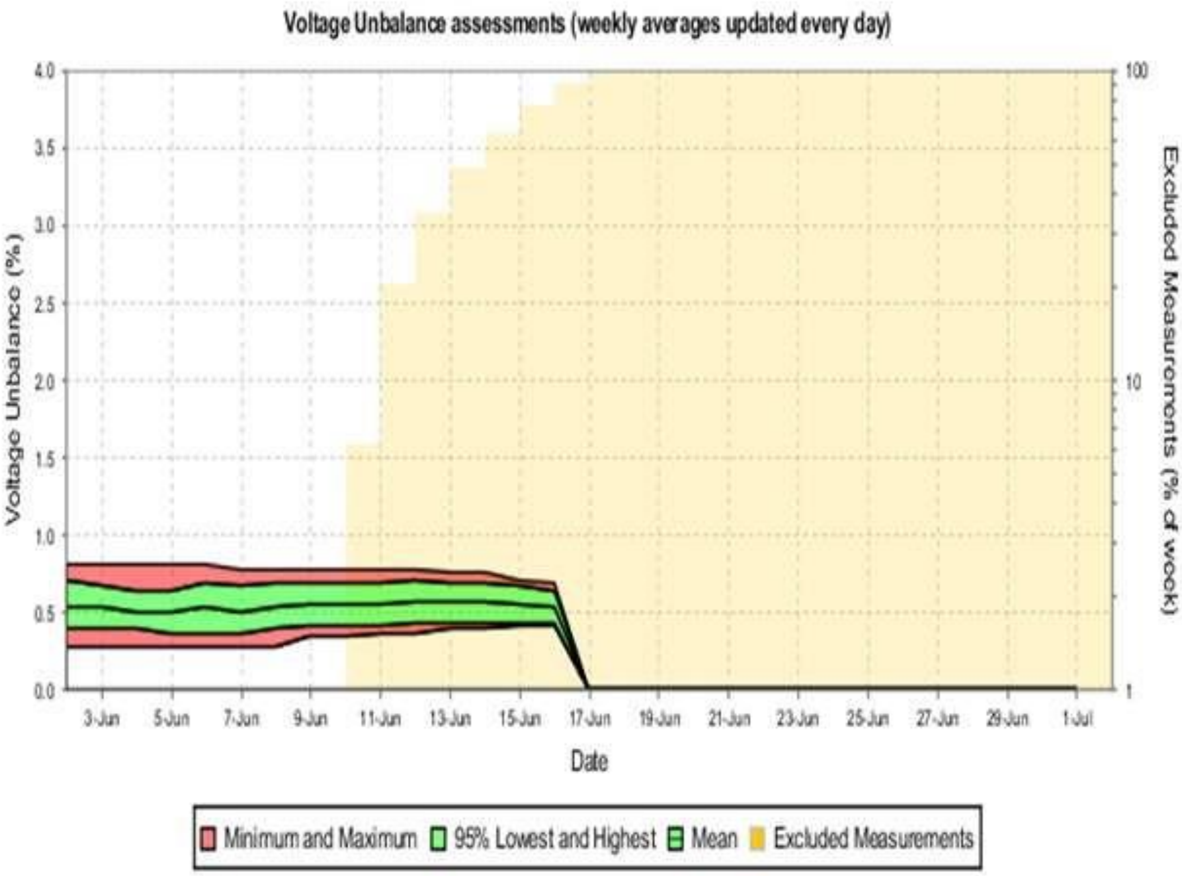


Figure 4.1: Voltage Unbalance Weekly Assessments

4.2 Flicker of Houhoek 66kV Compliance with NRS048-2:2003

Flicker measurements are assessed according to NRS048-2:2003 section 4.2.7. These 7 day sliding assessments are compared to the specified compatibility and limit criterium values day by day. Compliance over the whole time period is presented as percentages of the time that each criterium is met.

Table 4.2: Flicker Weekly Assessments

First Day	Last Day	Max	95% Highest	Ave	95% Lowest	Min
2017/05/28	2017/06/03	0.8	0.5	0.1	0.1	0.0

Compatibility Criterion	Compliance Level	Worst Assessment	Compliance	Non Compliance
95% highest	1.00	0.89	100%	0.0%

4.3 Power Frequency of Houhoek 66kV Compliance with NRS048-2:2003

Power Frequency measurements are assessed according to NRS048-2:2003 section 4.2.3. These 7 day sliding assessments are compared to the specified compatibility and limit criterium values day by day. Compliance over the whole time period is presented as percentages of the time that each criterium is met.

Table 4.3: **Power Frequency Weekly Assessments**

Heading	Heading	Heading	Heading	Rands
Minimum Weekly Value	49.00Hz	49.78Hz	100.0%	0.0%
Maximum Weekly Value	51.00Hz	50.20Hz	100.0%	0.0%

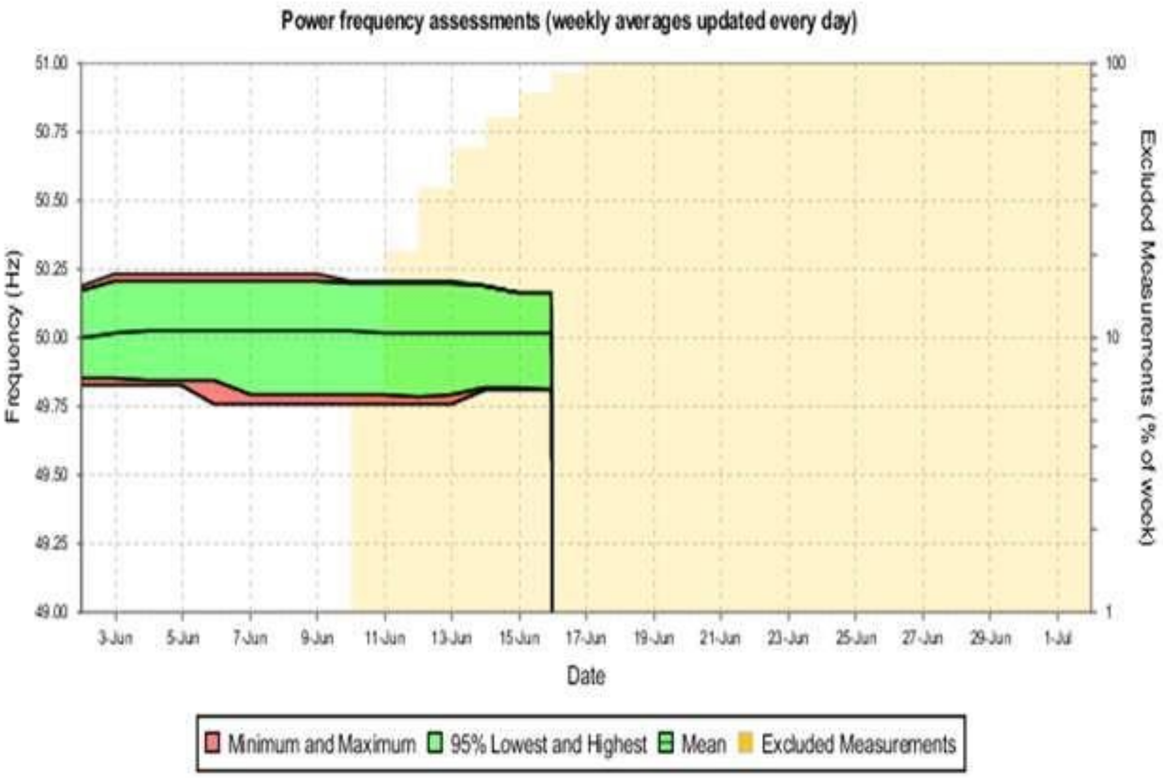


Figure 4.2: **Power Frequency Weekly Assessments**

4.4 Harmonics Weekly Assessments

Total Harmonic Distortion (THD), assessed according to NRS048-2:2003 section 4.2.5.2, are presented as day by day trends over the whole period. The assessment can be compared to planning, compatibility and limit values.

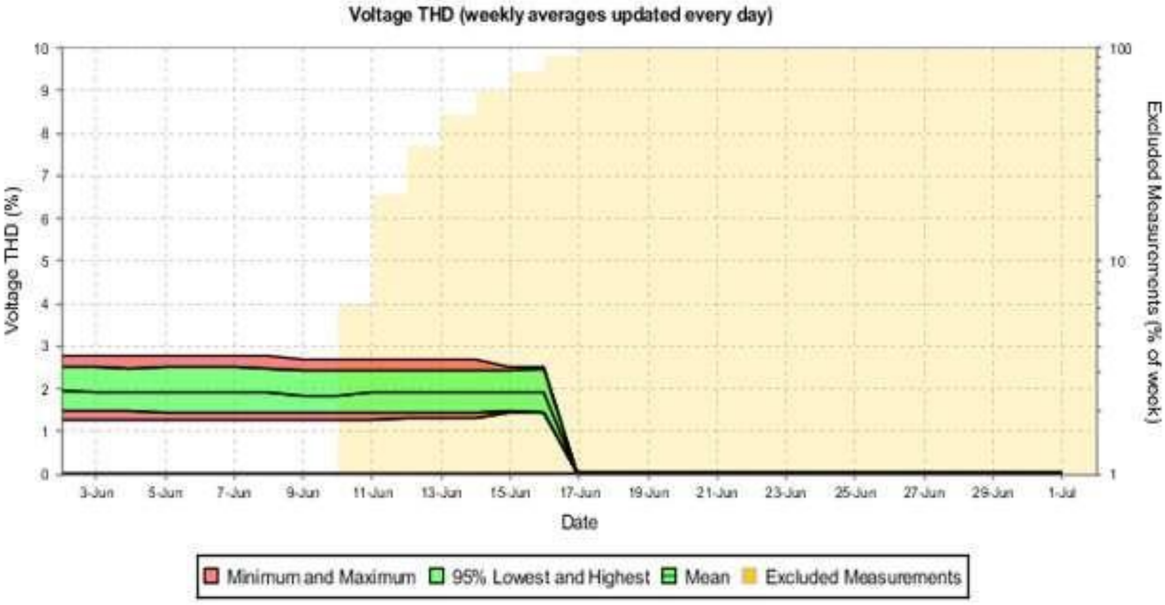


Figure 4.3: **Harmonics Weekly Assessments**

Table 4.4: **Harmonics Weekly Assessments**

First Day	Last Day	Max	95% Highest	Ave	95% Lowest	Min
2017/05/26	2017/06/01	2.7%V	2.5%V	1.9%V	1.5%V	1.3%V

Compatibility Criterion	Compliance Level	Worst Assessment	Compliance	Non Compliance
Maximum weekly THD	8.0%V	2.7%V	100%	0.0%

4.5 Summary

This chapter presents the results obtained from Dassiesklip 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 Houhoek 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.

Measurements were taken for a month and downloaded weekly for analysis. The data collected was similar for all four weeks of data collection; hence only one week data is presented and interpreted. 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.

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, taking measurements from each wind turbine would require nine 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.

CHAPTER FIVE

MODELLING WIND TURBINES WITH ENERGY STORAGE USING DIGSILENT

The existence of the Power Quality problems due to the installation of wind turbines with the grid is expressed. Battery storage provides a rapid response for either charging or discharging the battery and also acts as a constant voltage source for the critical load in the distributed network.

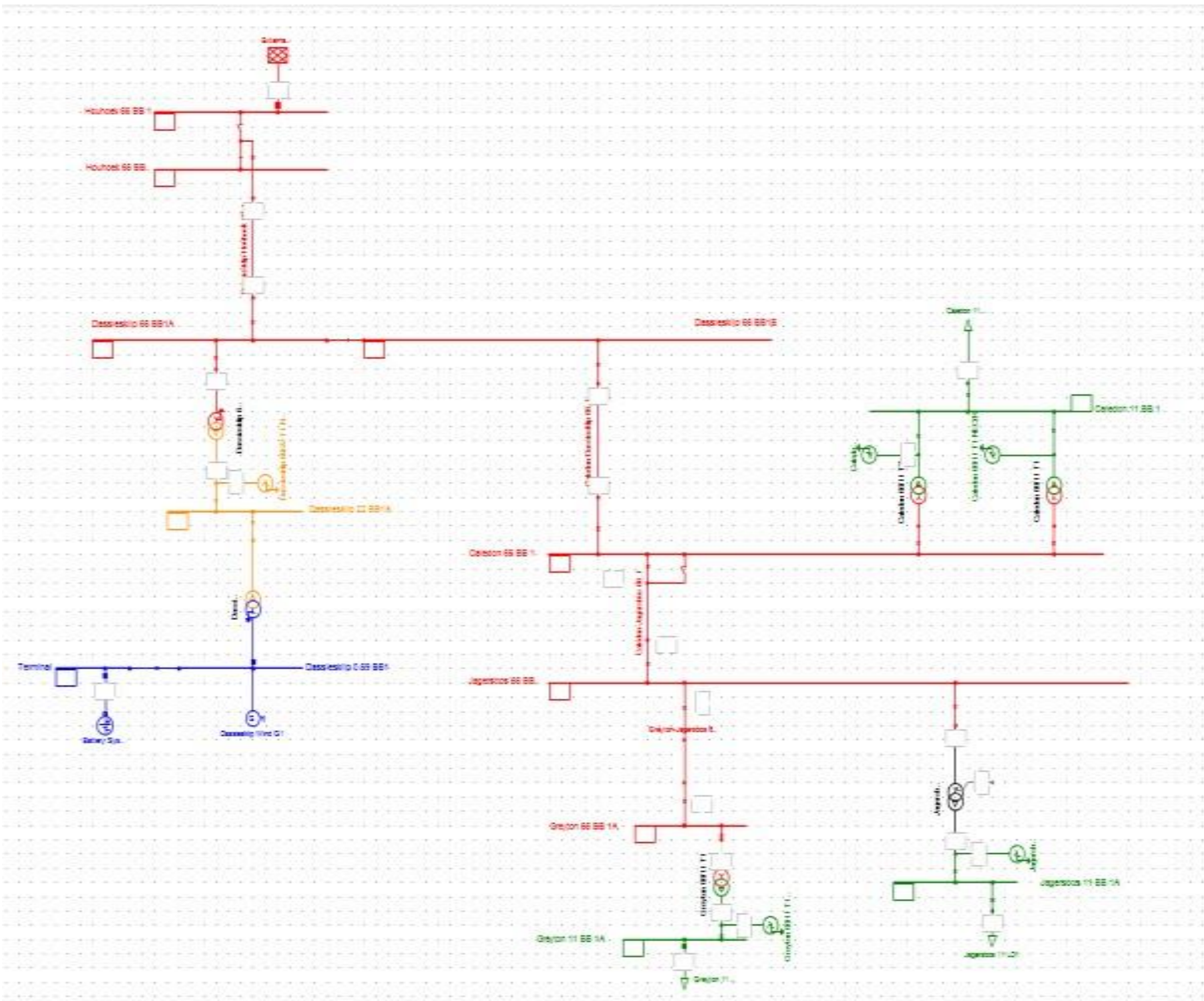


Figure 5.1: DigSilent Modelled Network with Energy Storage

5.1 Load Profiles

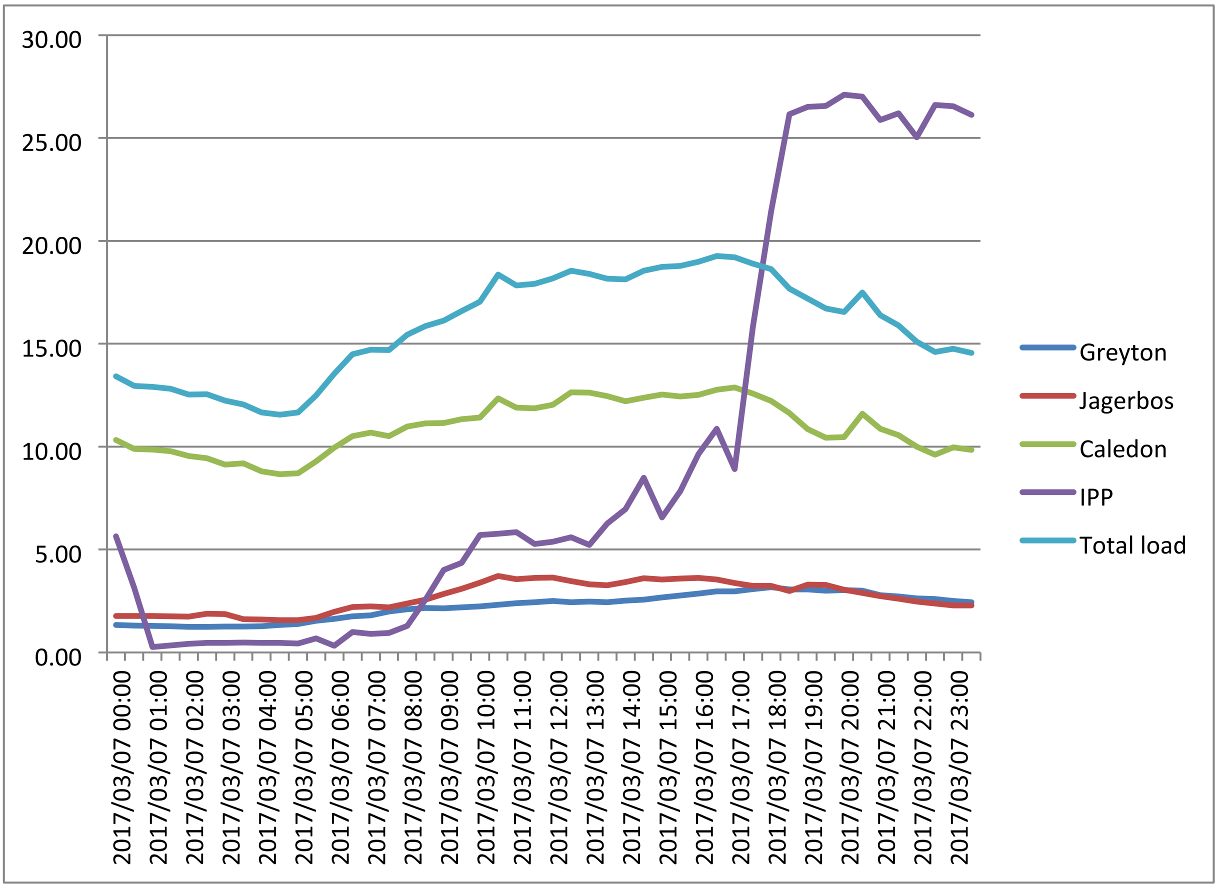


Figure 5.2: Load Profiles

Figure 5.2 shows different load profiles as per the modelled network. The load changes based on times of the day and the changes in wind speed is clearly shown

5.1.1 Load Profile with Wind Farm

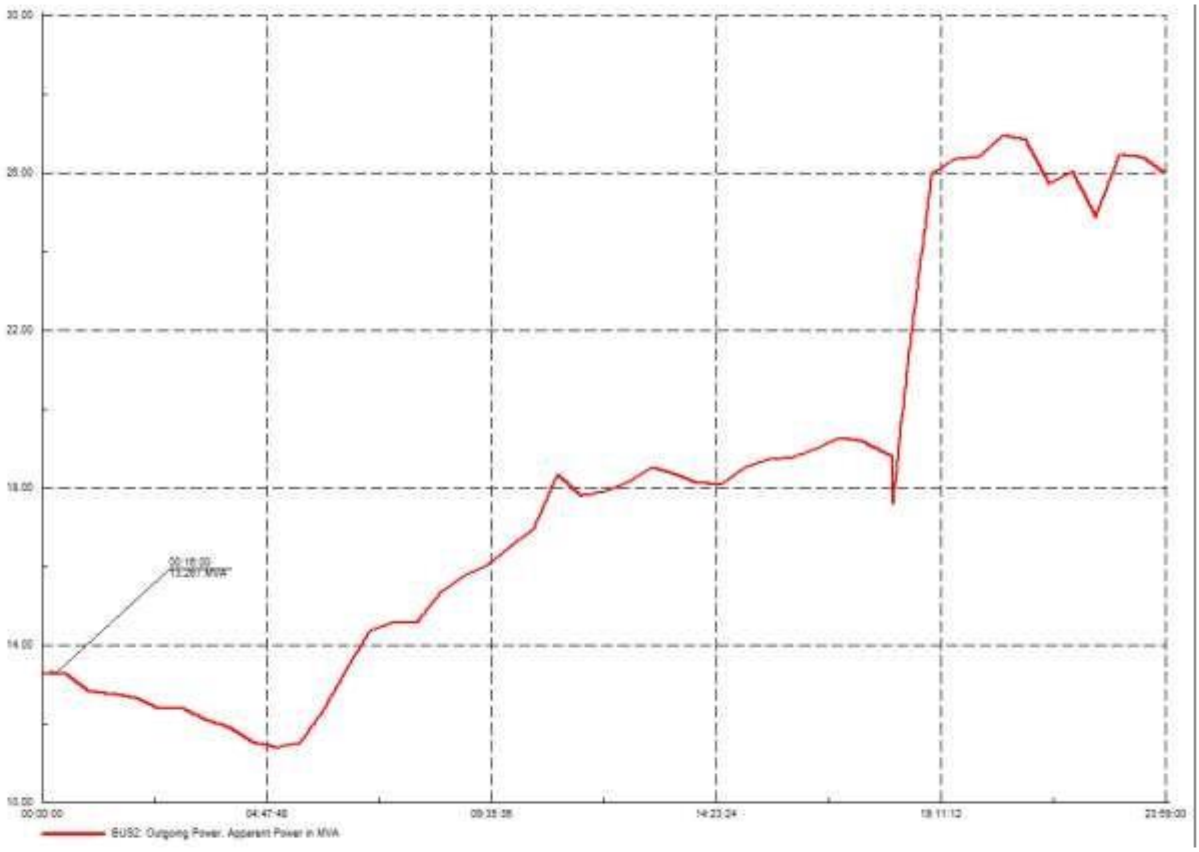


Figure 5.3: **Load Profile with Wind Farm**

Figure 5.3 shows the load profile with Wind Farm connected to the grid. This is before the energy storage is in operation to assist the wind farm.

5.1.2 Load Profile with Wind Farm and Energy Storage

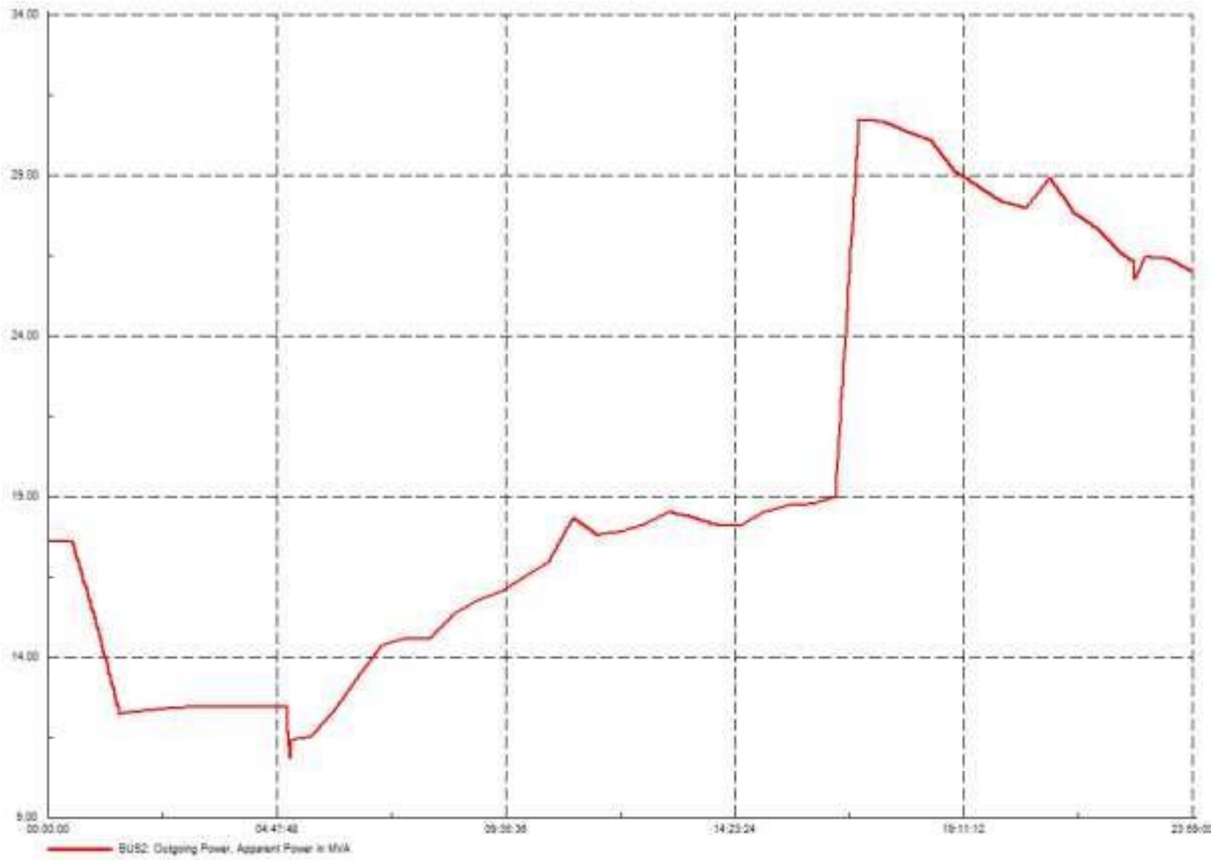


Figure 5.4: **Load Profile with Wind Farm and Energy Storage**

Figure 5.4 shows load profile with both wind farm and storage in operation. The times of the day where load changes show improvement when the storage is in collaboration with wind farm.

5.1.3 Load Profile Comparison

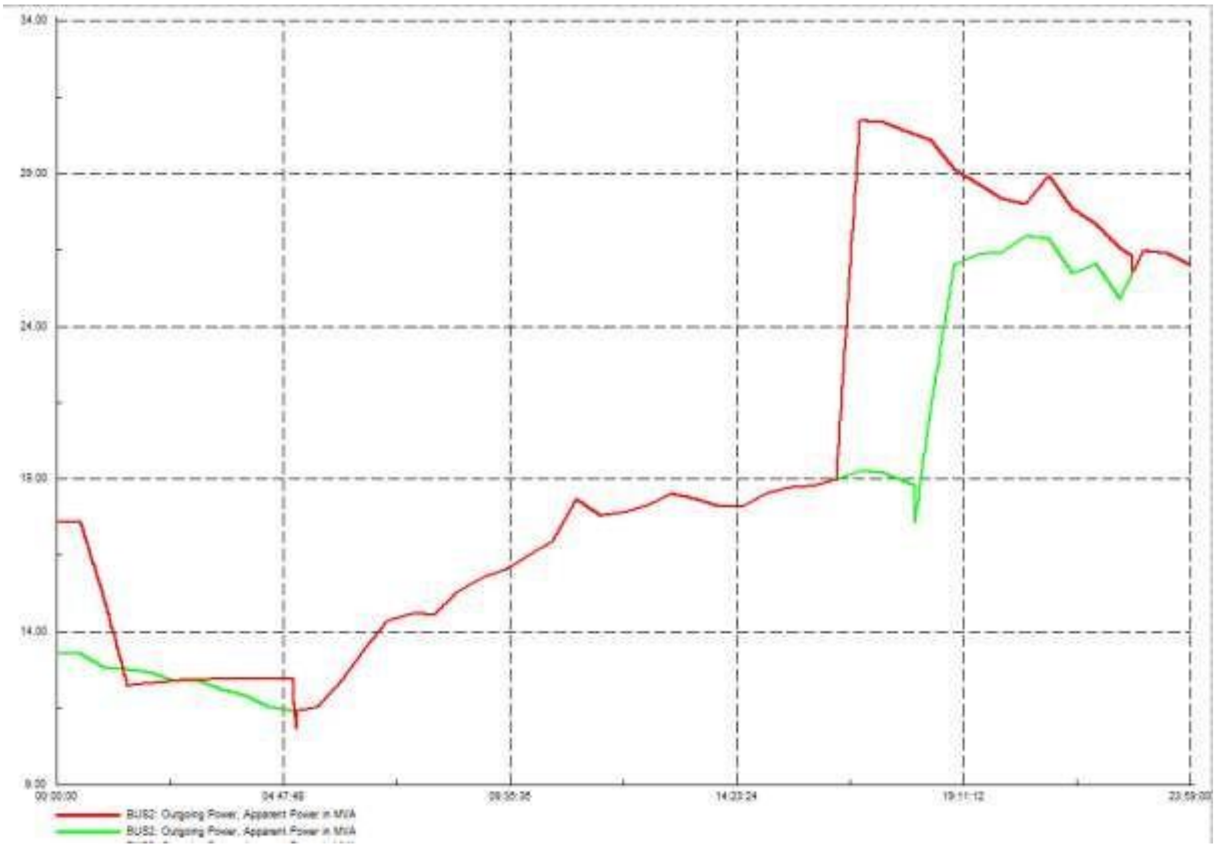


Figure 5.5: **Load Profile with Wind Farm and Energy Storage**

Figure 5.5 shows the comparison in load profile with and without the storage. The improvement is clearly showing when the storage is in operation. The time base improvement in relation to wind speed is clearly showing.

5.2 Applications of Energy Storage for Wind Power Plant and Grid Support

Operation of energy storage as a part of wind power plant can not only reduce power fluctuations but also enable introduction of wind power plant into new markets. The challenge of wind power resources integration is not a significant issue as long as the penetration rates are small, typically <10%. As penetration increases and becomes >20% of the load, there is required added regulation and spinning reserve resources to assure grid stability control. What is more, increased wind generation might reduce the regulation capability of the control area by displacing other generation units (usually the less economical ones). Grid operator may mandate that all the wind generators have to meet certain stability requirements as a condition for grid access (EPRI-DOE Handbook Supplement, 2007). Energy storage systems can be applied to the wind resource in order to provide all or some portion of the additional regulation control and spinning reserves (EPRI-DOE Handbook Supplement, 2007).

5.2.1 Applications imposed by Grid Codes

5.2.1.1 Grid Frequency Support

The purpose is to suppress fluctuations of the frequency in a grid which have a source in imbalance between generation and load (EPRI-DOE Handbook Supplement, 2007). In grids with high wind penetration, sudden reduction of wind power can contribute to frequency drop. It is possible to support grid frequency without energy storage in certain range by utilizing droop control and rotor inertia. With Energy Storage, frequency can be controlled without any curtailments of wind power.

5.2.1.2 Production Predictability

The predictability of the production from a wind power plant depends on the quality of the weather forecast and of the service forecast (Korpås, 2004). Forecast accuracy is dependent on time scale, site and season. In some countries forecast is required, however there are rarely any penalties if forecast is incorrect. In other markets, like Spain, there are penalties imposed on wind energy suppliers when generation does not match amount of generation bid for delivery (EPRI-DOE Handbook Supplement, 2007). Production predictability can be improved with energy storage which can compensate to some extend unforeseen changes in the wind (Korpås, 2004). This service requires that wind energy in excess of bid amounts is stored and released when the amount of wind power is insufficient.

5.2.1.3 Voltage Control Support

Maintaining adequate reactive power is crucial for voltage stability. This service can be obtained by full scale converter connected to the grid without energy storage; however addition of energy storage is improving regulation performance.

5.2.1.4 Low Voltage Ride Through (LVRT)

During the disturbance in the grid, wind turbines have to keep running for certain period of the black grid. This supports grid reinstatement. Again LVRT can be done without energy storage but it requires additional devices and/or curtailments in power production in order to keep voltage on the DC link capacitor in safe range. Addition of energy storage can support LVRT by charging energy storage during fault and protect the DC link capacitor against overvoltage.

5.3 Summary

Energy Storage is a capture of energy produced at a particular time and to be used at a later stage to reduce imbalances between energy demand and energy production. Energy Storage includes converting energy forms that are difficult to store to forms that are conveniently easier and economically storable.

This chapter talks to the addition of battery storage for the mitigation of power quality problems. Load Profiles showing comparison of before and after the battery storage is integrated are demonstrated. The time based improvement in relation to wind speed is clearly demonstrated.

Energy Storage allows for better use of renewable energy. The use of batteries to store energy is a necessity, in ensuring that power can be used whenever needs be.

CHAPTER SIX
CONCLUSIONS AND RECOMMENDATIONS

6.1 Power Quality

From the studies conducted, it can be seen that the Dassiesklip wind farm will not conform the power quality requirements from a harmonic point of view, because of a 17th harmonic violation.

Three ways of overcoming the problem were investigated namely:-

- Reducing the Dassiesklip 66/22 kV transformer impedance
- Installing a shunt capacitor on the 22 kV busbar at Dassiesklip
- 17th harmonic filter

Reducing the transformer impedance moves the resonance point to a higher frequency and the addition of shunt capacitors moves the resonance point to lower frequencies. The higher frequency is not an issue as no harmonic currents are given beyond the 17th and it is thus assumed that the WEF does not generate harmonics above the 17th harmonic. The reduced transformer impedance option is thus technically acceptable. Two of the shunt capacitor options studied (0,2 and 0,3 Mvar) are acceptable as they ensure the harmonic distortion is within limits, up to, and including, the 17th harmonic.

The most acceptable shunt capacitor appears to be the 0,2 Mvar as the harmonic distortion is the least up to the 17th harmonic. The shunt capacitor lowers the resonant frequency. Installing a filter will result in two resonant frequencies instead of one; one frequency is greater than the 17^{th} harmonic and the other below. As the filter causes a resonance below the 17th harmonic, no advantage is seen over a 0,2 Mvar shunt capacitor.

It is recommended that a 0,2 Mvar shunt capacitor be installed on the 22 kV busbar at Dassiesklip to meet harmonic requirements while the Eskom network fault current is 2,8 kA on the Dassiesklip 66 kV busbar.

On account of the Eskom network having a possible 15th harmonic current source, it is further recommended that Eskom be informed of a possible 15th harmonic violation due to harmonics in their network.

A problem will exist with harmonics when the fault level is raised to the future maximum level. However, if the capacitor is taken out of service when all network infrastructure upgrades are completed, all harmonics are well below the lesser of the "ESKOM DISTRIBUTION CONNECTION AND USE-OF-SYSTEM AGREEMENT

WITH GENERATORS" and NRS 048 Planning Limits. It can therefore be concluded that the Dassiesklip Wind Farm should easily conform to the harmonic requirements at the 66 kV busbar at Dassiesklip substation with the future fault levels, without any intervention such as shunt capacitors, filters or transformer impedance reduction.

The Wind Farm will conform to the flicker requirements. The wind farm will also meet the rapid voltage change limit if it is assumed to be operating at unity power factor before it is switched off.

6.2 Energy Storage

Electrical energy storage is one of the most promising solutions to the challenges related to wind integration. Storage solutions require significant investments and are introducing energy losses to WPP. These features have to be weighed against the benefits that storage can provide.

There are many types of ES technologies described in this research with different potential, characteristics and different applications, but none of them is able to solve all problems of wind power integration in power system. Particular ES selection is application and timescale dependent and for WPP should be considered in relation to services that are demanded. It can be seen that from the comparison of storage technologies in respect to applications, the best choices for WPP integration seems to be: PHES, CAES, LIES, FBES, NaSES and LAES. However PHES and CAES technologies placement are dependent of geological issues. Hydrogen seems to have a huge potential in a future, however present state of development of this method makes it less efficient and very expensive solution for WPP. Supercapacitors with combination with battery can be a good solution because of their very high cycling possibility. It looks like LAES are less relevant for WPP integration than LIES, NaSES and FBES mainly because of smaller energy density, smaller depth of discharge and big sensitivity to temperature changes.

The main barriers for widespread commercial implementations of ES with WPPs are high cost of ES technologies, immaturity of some technologies and uncertainty over the quantified benefits. Government subsidies for ES would also speed up widespread use of the new ES installations with WPPs.

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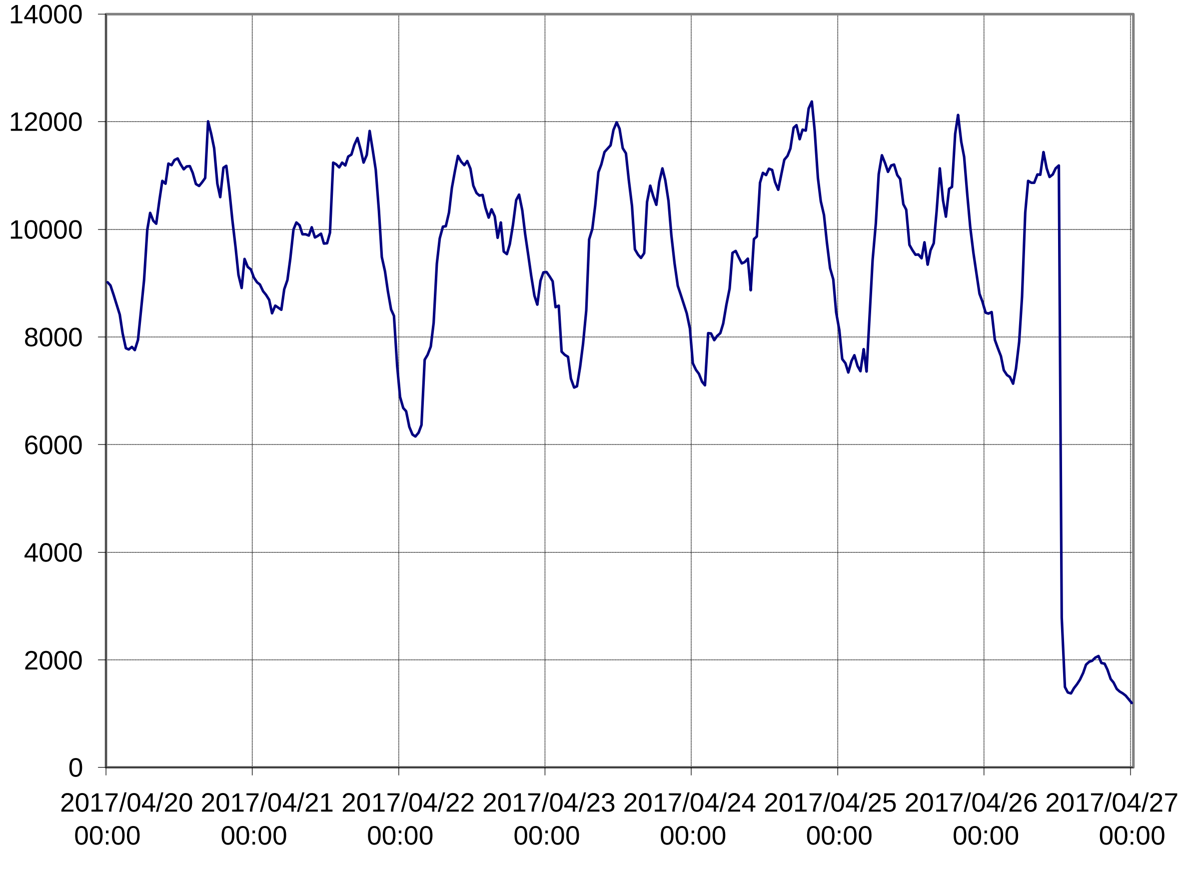
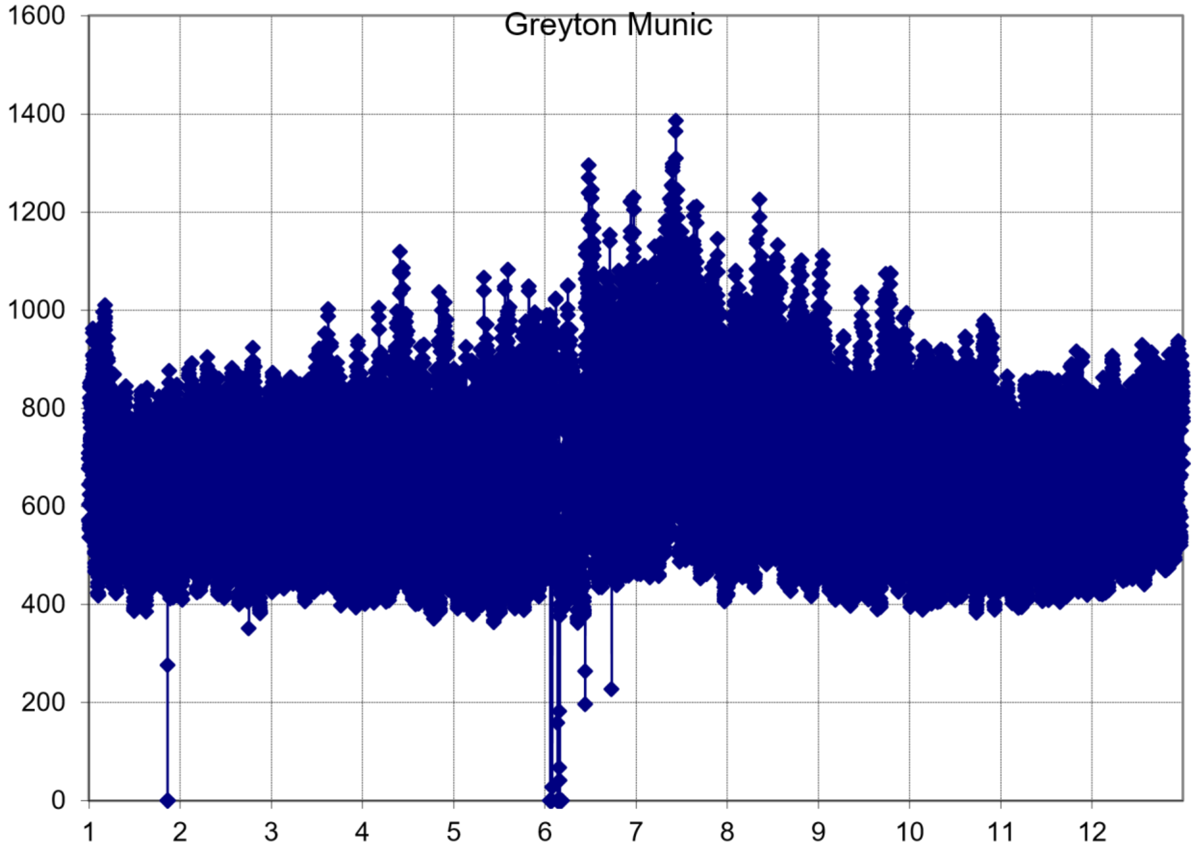
APPENDICES

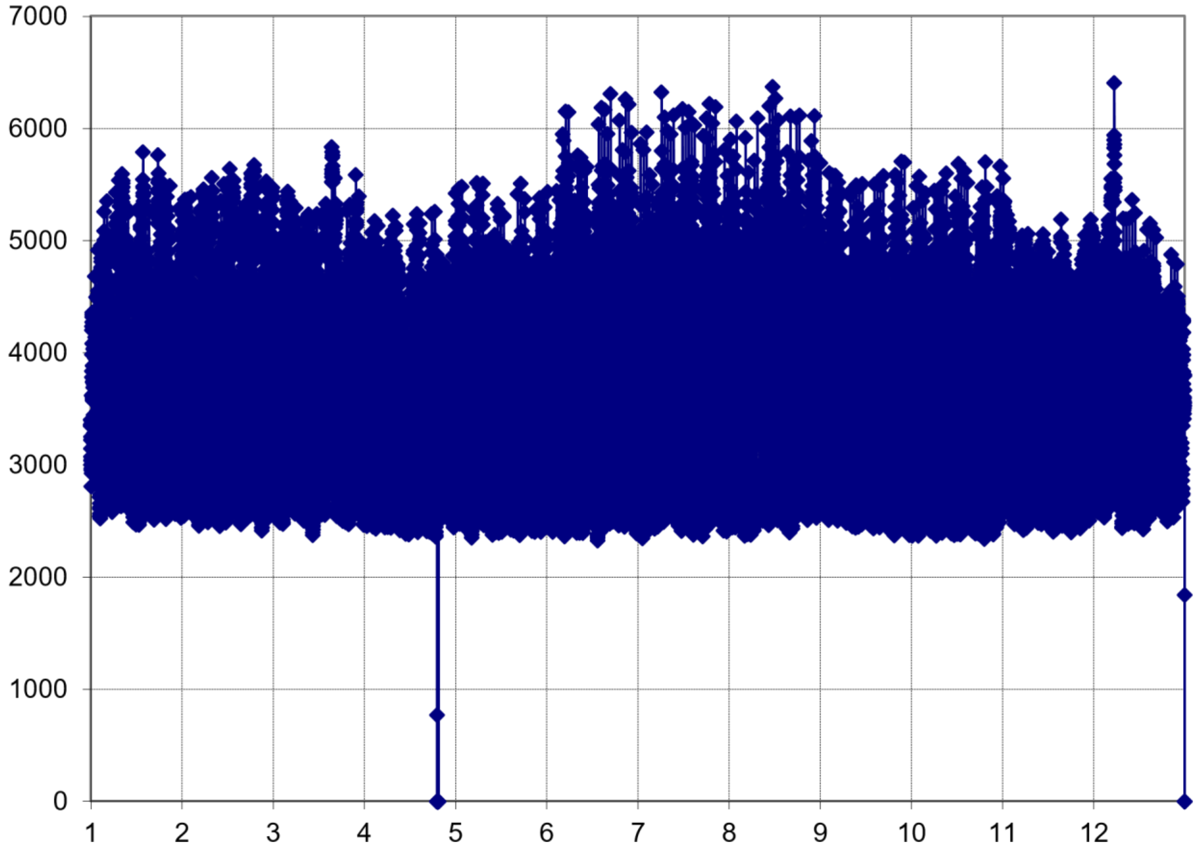
APPENDIX A: CALEDON WEEKLY LOAD



APPENDIX B: GREYTON MUNIC LOAD



APPENDIX C CALEDON MUNIC LOAD



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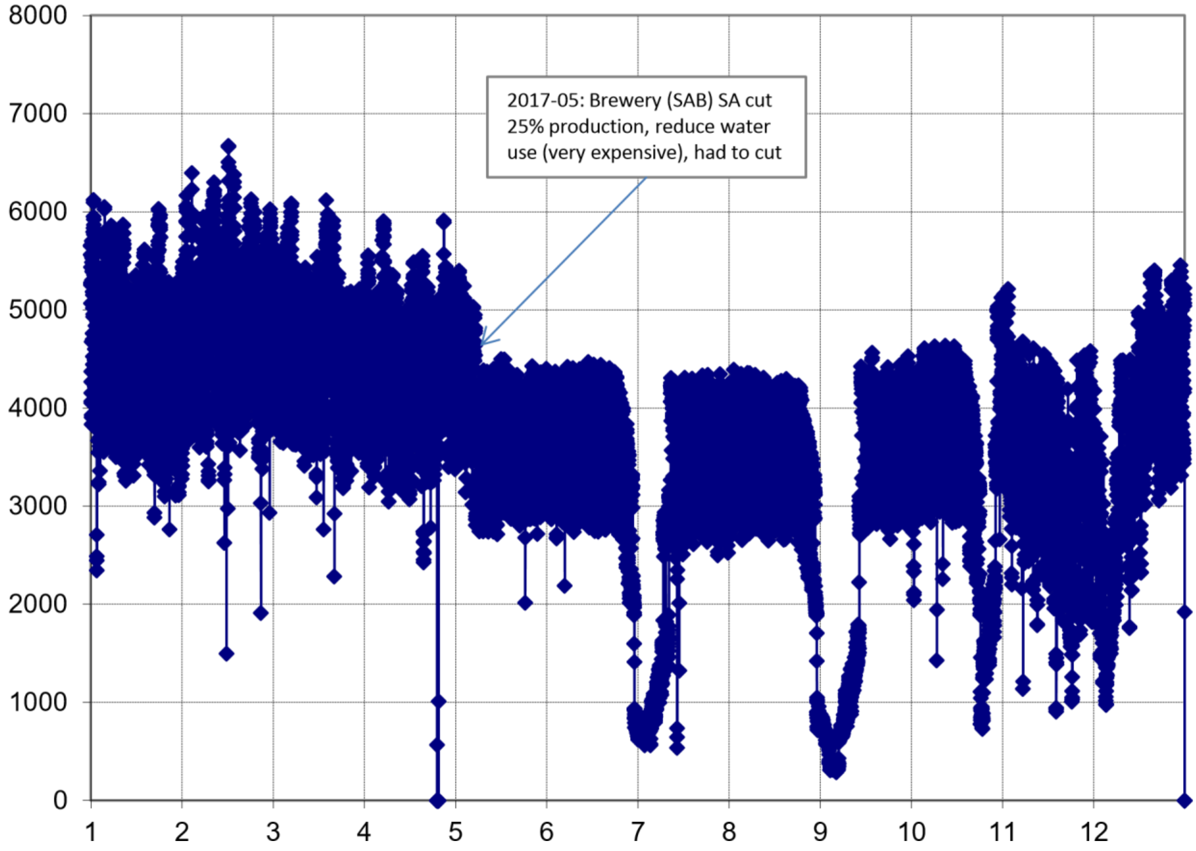
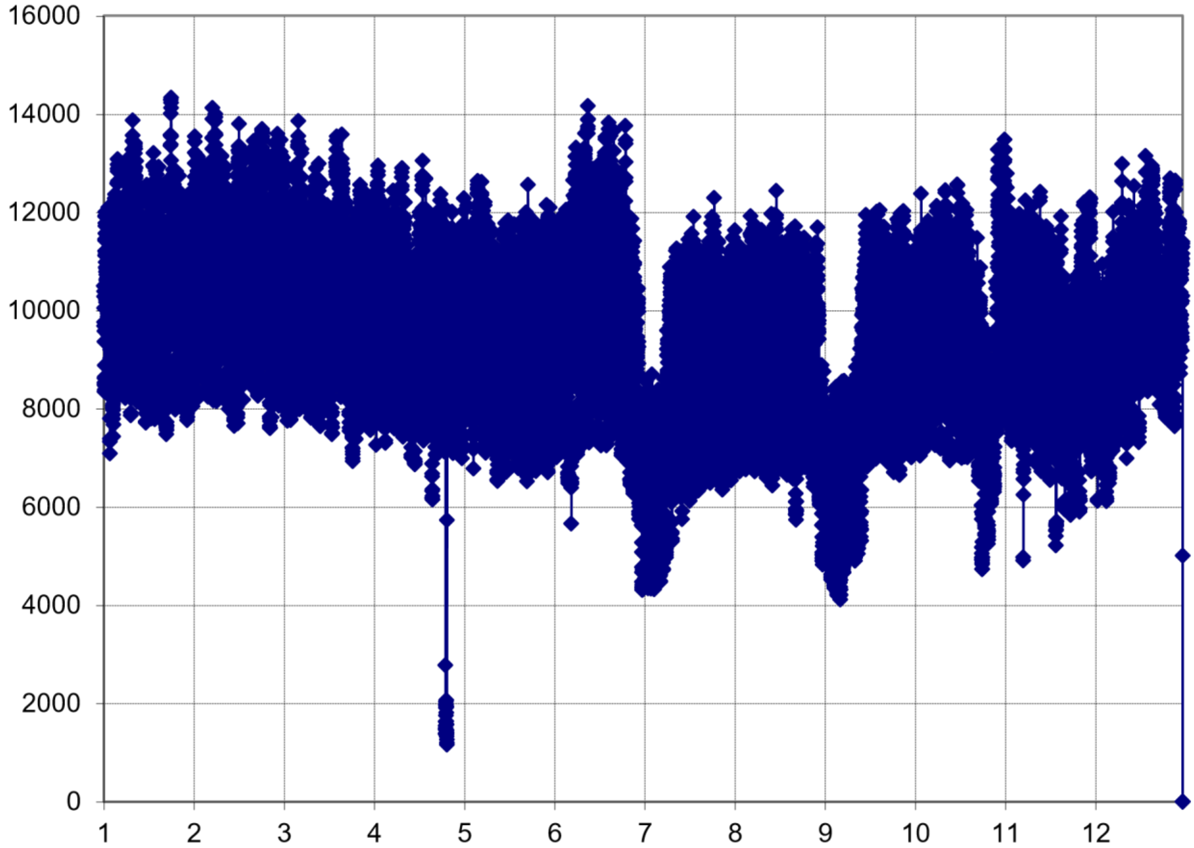
APPENDIX D: SAB LOAD CALEDON



APPENDIX E CALEDON LOAD



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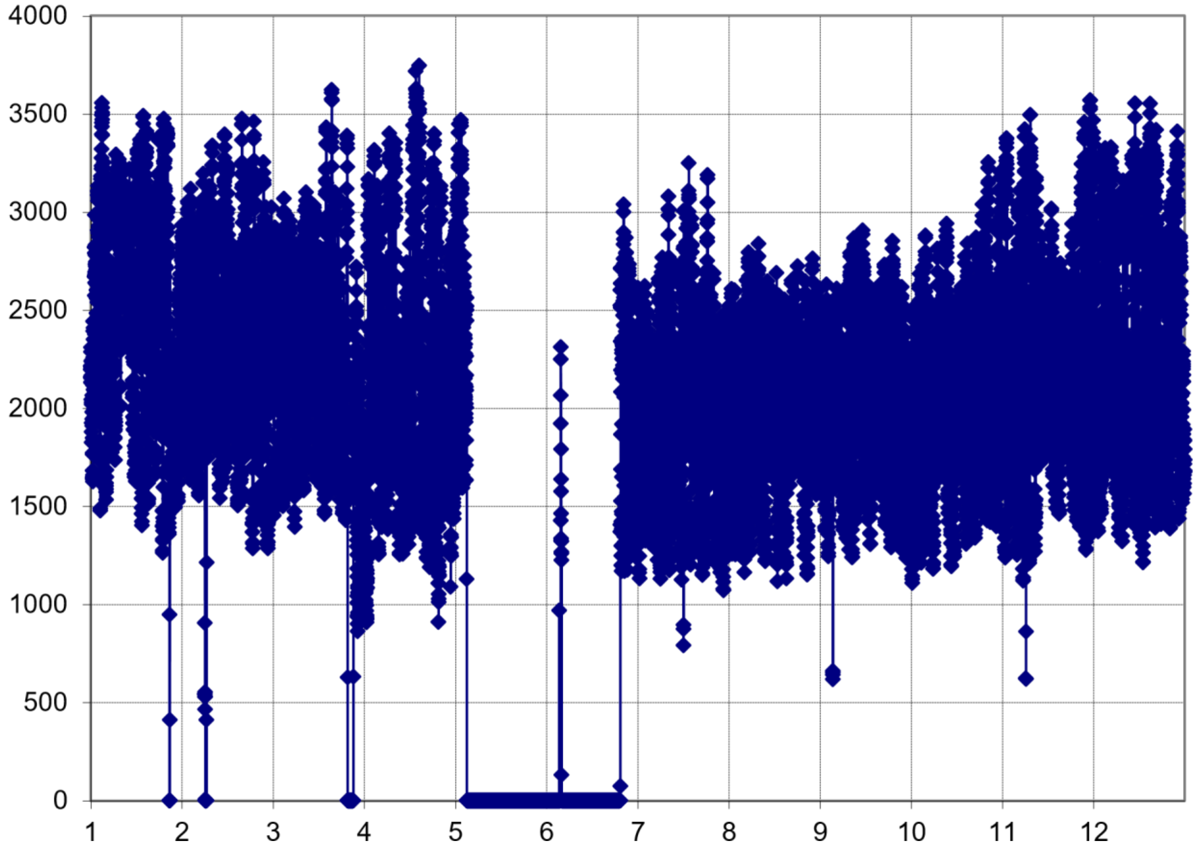
APPENDIX F JAGERSBOS LOAD



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APPENDIX G GREYTON LOAD