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Mitigation of operational risk in South African distribution networks with integrated renewable generation

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DECLARATION

I, GN Esterhuysen hereby declare that the dissertation entitled “Mitigation of operational risk in South African distribution networks with integrated renewable generation” and the material therein is my own original work except where specific reference is made by name or in the form of a numbered reference. The work herein has not been submitted to any other university or institution for examination.

GN Esterhuysen

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Signed on the 19 day of November 2018 at Bloemfontein

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I want to thank God for the ability to continue my studies, all honour and glory to Him. To my loving wife, Anri and daughters, Nina and Lise, thank you for all the support and sacrifices you made to give me the time to complete this. To Willem, who has been my mentor at Eskom for almost 10 years, thank you for all the encouragement and support. Lastly, to Prof Rens for his guidance and advice.

ABSTRACT

Under the Department of Energy's (DoE) renewable energy independent power producer procurement program (REIPPPP), utility scale renewable energy projects were connected to sub-transmission networks. To date 4138 MW of renewable energy has been commissioned.

All renewable energy (RE) generation must comply with the RE grid code in South Africa. This ensures a predictable response of the RE facility under normal, weak and fault conditions. As the penetration level of RE generation increased, the requirements imposed on the RE generators also increased and become more advanced.

However, even with fully grid code compliant RE facilities, there are operational risks. This study explores the operational risks to both the network service provider (NSP) and the RE generators, especially under weak grid conditions.

The operational risks include voltage control under normal and weak grid conditions, RE generation stability connected on traction networks, the response of RE generation during faults and the prevalence of supraharmonics present in the sub-transmission network as a result of RE generation.

The objective of this study is to determine the operational risks associated with RE generation operating on sub-transmission and distribution networks; provide mitigating solutions for operational plants and offer recommendations for future connections.

Keywords: renewable generation, distributed generation, operational risk, weak grids, voltage control, supraharmonics, voltage ride through

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AC	alternating current
AGUP	Grid unavailability period
ARC	automatic reclose cycle
BEE	Black economic empowerment
BRICS	Brazil, Russia, India, China and South Africa
COD	commercial operation date

COP21	21st Conference of the Parties singed in 2015
COW	Clerk of works
CSP	Concentrated solar plant
CT	current transformer
DC	direct current
DCUOSA	Distribution customer use of system agreement
DFIG	double fed induction generator
DNOP	Distribution network operations planning standard
DoE	Department of Energy
DS	Distribution system
DSO	Distribution system operator
EHV	Extra high voltage
EU	European Union
FM	frequency modulation
GAU	Grid access unit
GCAC	Grid code advisor committee
HGHL	High generation, high load
HGLL	High generation, low load
HV	High voltage
HVRT	high voltage ride through
ICE	indicative cost estimate
IGBT	insulated gate bipolar transistor
IPP	independent power producer
IRP	Integrated resource plan
LED	light emitting diode
LGHL	Low generation, high load
LGLL	Low generation, low load
LV	low voltage
LVRT	low voltage ride through
MD	maximum demand
MEC	Maximum export capacity
MPPT	Maximum power point tracking
MTS	main transmission station
MV	medium voltage

MW	Megawatt
n-1	single network contingency
NEC	neutral earthing compensator
NERSA	National energy regulator of South Africa
NMD	notified maximum demand
NSP	Network service provider
OHL	Overhead line
OLTC	On load tap changer
OPM	operations procedure manual
PCC	point of common coupling
PF	power factor
PLC	power line carrier
PoC	Point of connection
PPA	Power purchase agreement
PPC	Power plant controller
pu	per unit
PV	Photovoltaic
PWM	Pulse with modulation
QoS	Quality of supply
RE	Renewable energy
REBIT	Renewable energy bit in tariff
REIPPPP	Renewable energy independent power producer procurement program
RETEC	Renewable energy technical evaluation committee
RPP	Renewable power plant
SBO	Single buyer's office
SCADA	Supervisory control and data acquisition
SCR	short circuit ratio
SCSC	series grid side converter
STATCOM	static synchronous compensator
SVC	static VAr compensator
TEF	Technical evaluation forum
THD	total harmonic distortion
TS	transmission system
TSO	transmission system operator

UHF	ultra-high frequency
VRT	Voltage ride through
VSD	Variable speed drive
VT	voltage transformer
VVT	Voltage variation test
WEF	Wind energy facility

LIST OF SYMBOLS

P	active power (W)
Q	reactive power (VAr)
X	reactance (Ω)
R	resistance (Ω)
S	apparent power (VA)
V	voltage (V)
I	current (A)
U_B	voltage unbalance (%)

CHAPTER 1 INTRODUCTION

1.1 Background on renewable integration in South Africa

Department of energy (DoE) launched the renewable energy independent power producer procurement program (REIPPPP) in 2011 to encourage private investment in the energy sector and to fulfil the commitment to COP21 and the Paris agreement in terms of carbon emissions [1], [2]. Renewable energy is also an integral part of the integrated resource plan (IRP), accounting for 18800 MW by 2030 [2].

Selection criteria mainly consist of a renewable energy bid in tariff (REBIT), weighing 70%. The other 30% consists of factors such as local content, black economic empowerment (BEE) and job creation [1]. The program is being rolled out in 5 rounds. Rounds 1 – 3 have been successfully completed in 2016/17. Round 4 commenced in 2018 after significant delays from 2016 and the bid window for Round 5 is planned to open beginning of 2019.

This program only considered utility scale renewable generation connecting to the sub-transmission (44 – 132 kV) and distribution networks (6.6 – 33 kV) with rated active power output of more than 1 MW.

End of 2018, 4138.25 MW of renewable energy has been commissioned through 79 projects [2], see Figure 1-1. Energy generated by the RE generation is purchased via the Single buyer's office (SBO) under a 20 year power purchase agreement (PPA).

Based on Eskom figures from May 2017, the total installed Eskom owned generation capacity is 47201 MW [3]. Included in this figure is 161 MW from Eskom-owned renewables compromising Sere wind farm (100 MW) and distributed Hydro stations (Colley Wobbles, First Falls, Ncora and Second Falls of combined 61 MW).

RE generation projects from Round 1 – 3 accounts for 4138.25 MW, or 8% of the installed capacity in SA as shown in Figure 1-2.

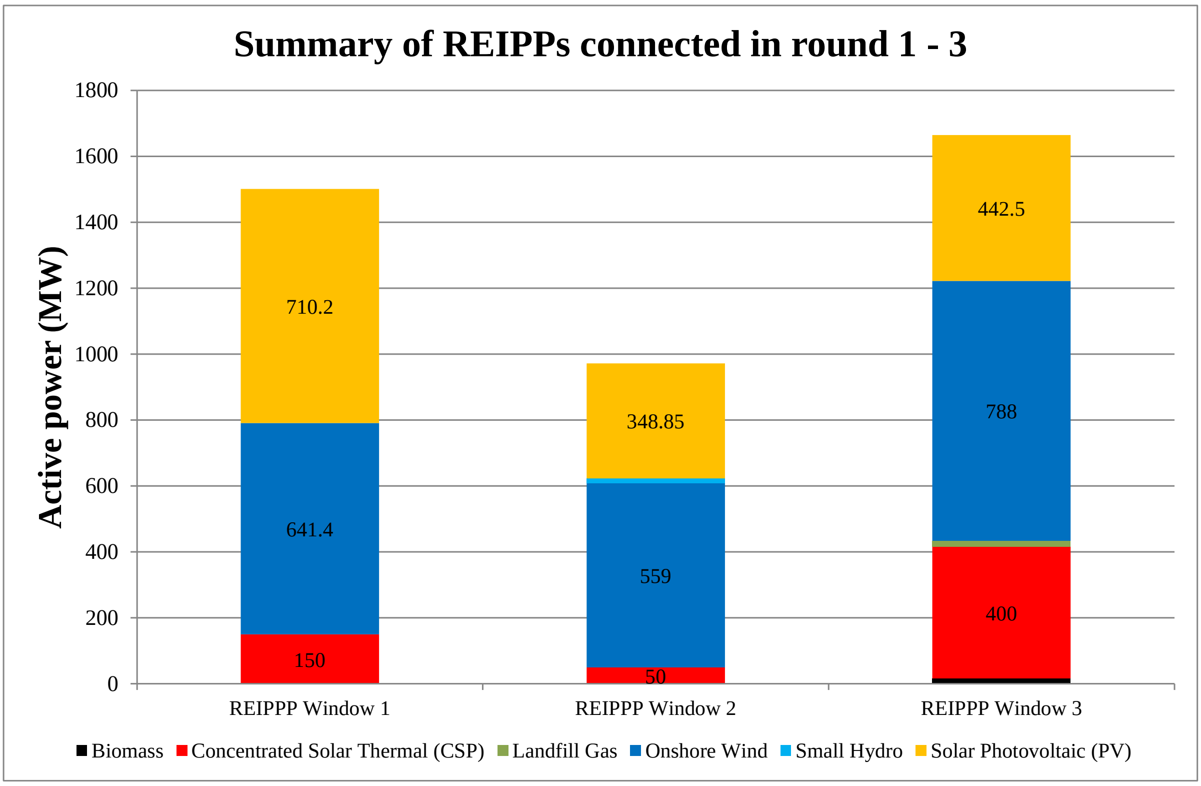

Figure 1-1: Summary of RE generation connected in rounds 1 – 3 [4]

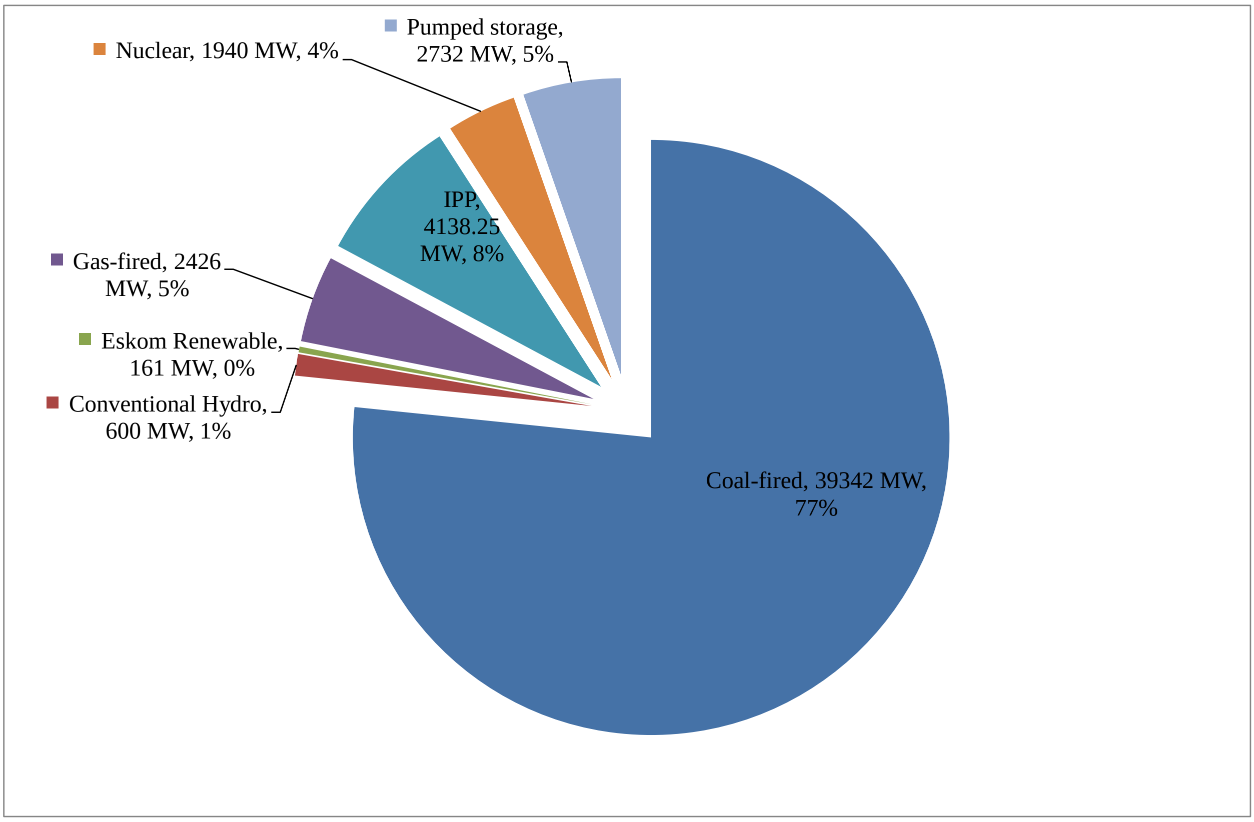

Figure 1-2: South African generation mix [3]

The national penetration level of RE is still low compared to leaders in renewable generation, being Denmark (42%), Portugal (23.2%), Ireland (23%), Spain (18%) and Germany (13.3%) [5]. Compared to other BRICS countries, South Africa is doing very good with RE. China has 3.3% and Brazil 3% [5].

1.2 Integration in sub-transmission and distribution network

Under the 20 year PPA, all renewable generation is non-dispatchable and managed by the relevant Distribution system operator (DSO). These RE sources are non-dispatchable due to the intermitted nature of the renewable energy source. Active power cannot be scheduled, but can be constrained by the DSO should the need arise.

Reactive power can be used to assist the local grid voltage. Reactive power control modes and set points are remotely set by the DSO via a SCADA interface. South African DSO’s have areas of responsibility as indicated below in Figure 1-3.

Eskom has six DSOs situated in Bellville, Bloemfontein, East London, Pietermaritzburg, Witbank and Germiston. Eskom’s National control (TSO – transmission system operator) is also situated in Germiston.

National control is responsible for frequency and voltage control and system security of the EHV network (765 kV – 132 kV). Regional DSOs are responsible for operator- and equipment safety and continuity of supply in HV and MV networks.

South African RE sources are often connected to remote rural networks [6] due to the availability of space and network capacity to host additional loading. These rural networks are often long lines that are lightly loaded with a low fault level and weak under *n*-1 conditions [6]. Weak grids are defined as networks with very low levels of short circuit power.

Figure 1-4 shows a map of round 1 – 4 RE projects. RE projects within the red dotted area is operated by Bloemfontein DSO and features as the main study area for this dissertation. It consists of mostly PV generation and some wind generation.

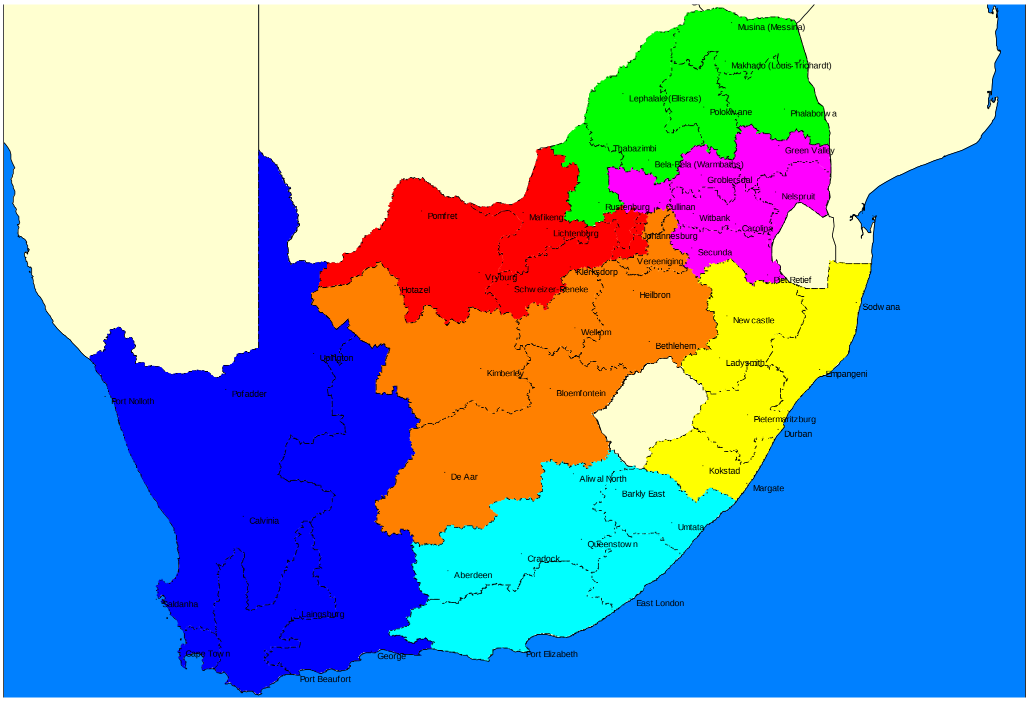

Figure 1-3: Eskom DSO layout

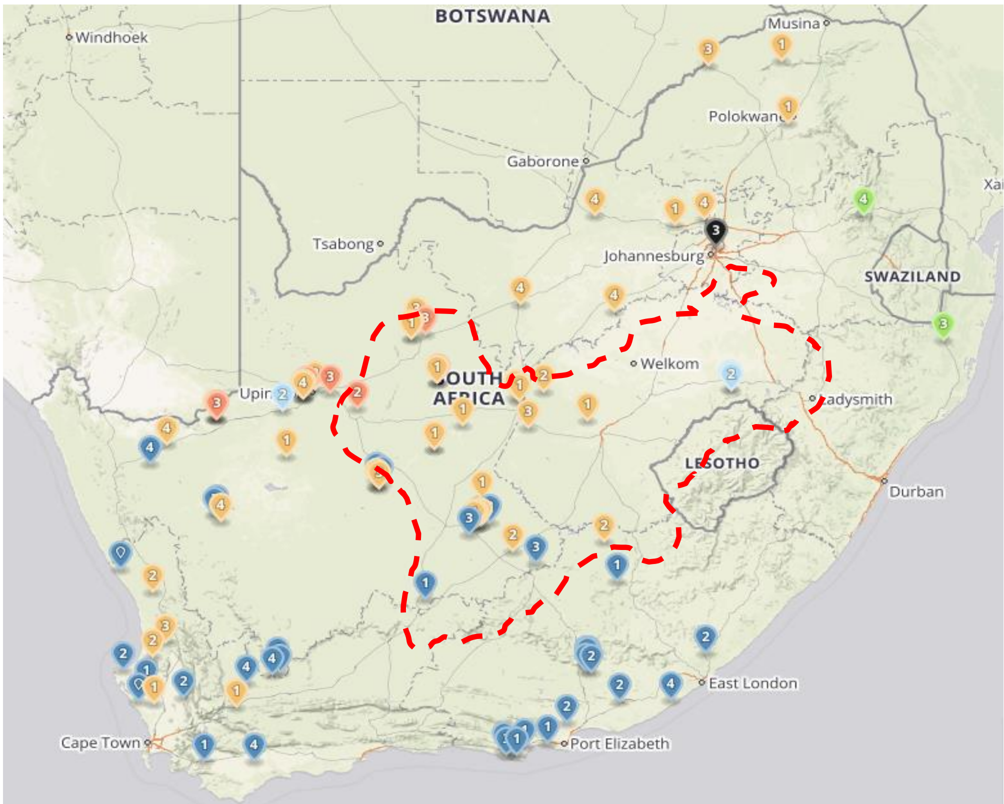

Figure 1-4: Map of renewable energy projects in South Africa [4]

1.3 Renewable energy grid code

Grid codes are a set of rules all RE generation must comply with in order to facilitate a grid connection. It specifies the minimum functionality in order to have a standard method of continuous operating and behaviour during grid disturbances. Since RE generation penetration levels have increased dramatically in recent years, one of the key aspects of the RE grid code is to impose synchronous generation response onto RE generation. This was made possible with the introduction of power electronics [5].

1.3.1 Utilization of power electronics in renewable energy

PV, wind and small hydro plants all use power electronic systems to inject energy into the grid [5].

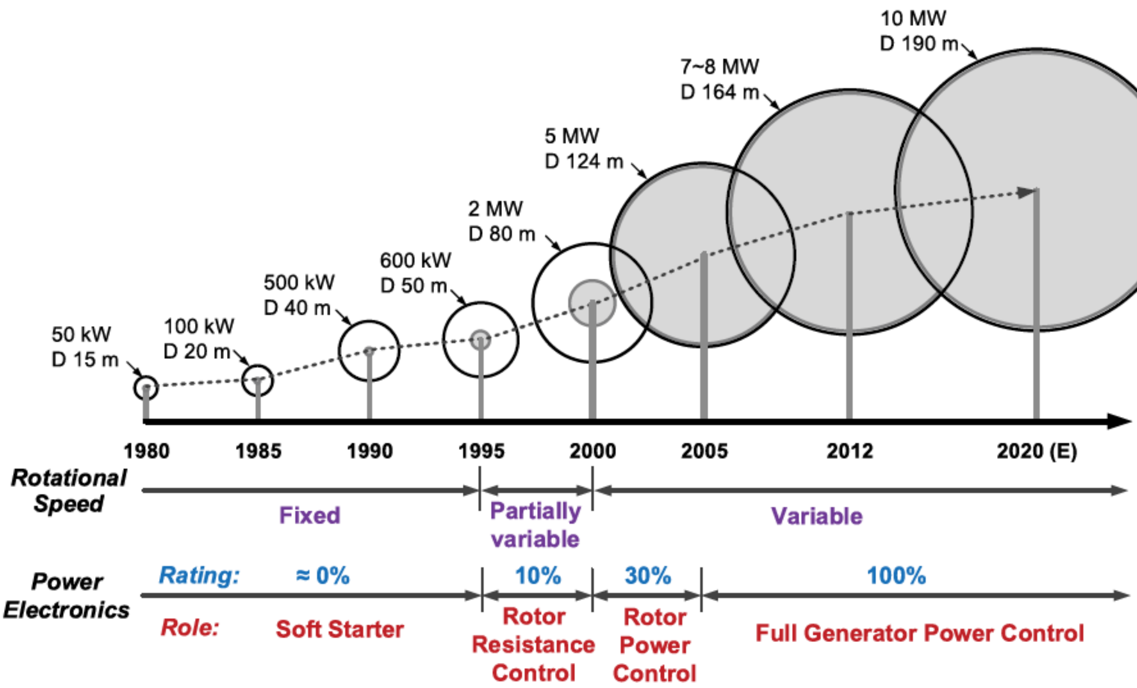

Figure 1-5: Role of power electronics in wind turbine development [5]

Figure 1-5 shows how power electronics were used in the development of wind turbines. First generation fixed speed wind turbines used power electronics as a soft starter; connecting the wind turbine to the grid during start up for squirrel-cage induction generators. Partially variable wind turbines used power electronics to reduce the mechanical stresses in the system by controlling the rotor resistance of wound-rotor induction generators.

With the introduction of DFIG, a partial power converter (30 % of rated power) is used in order to allow variable speed operation and provide ancillary services to the grid [5].

At present, state-of-the-art fully rated converter wind turbines is fast becoming the preferred choice for wind turbine installations due to its flexibility and ability to meet modern grid code requirements. [7]. Grid-connected battery storage applications also use power electronics to charge and discharge [8] the battery. Systems which can deliver a peak power of 200 MW and store 800 MWh are already in use in China [9].

As the demand for power converters grew, the capability of the converters also improved. An example of this is the low voltage ride through (LVRT) requirements. First generation wind facilities could not withstand voltage dips, nor was the ability to stay connected to the grid during a fault a requirement.

LVRT became a requirement because of the value it added to both the grid operators and the RE generators. LVRT functionality was successfully implemented by using power converters in type 3 and 4 wind turbines [5].

As RE facilities become bigger and more concentrated, the manipulation and control of reactive power also became essential in operating networks with high levels of RE generation [8].

Table 1-1 shows the benefits of integrating power electronics with renewable generation. As the advancement of power electronics increased, the capability (and wide spread grid acceptance) of renewable generation also increased.

Table 1-1: Advancements of renewable generation capability with the implementation of power electronics [8]

Grid integration features	Conventional power plants	Wind turbines with no/limited power electronics	Wind turbines with power electronics
Active power control	Good	Moderate	Good
Reactive power control	Good	None to moderate	Excellent
Power output inertia	Excellent	None	Good
Frequency control	Excellent	None	Excellent
Black start capability	Good	None	Good

These advances in power electronics are the enabler for advanced control features of renewable generators.

High frequency switching speeds of the power electronics used in power converters are also responsible for the prevalence of supraharmonics – frequencies in the range of 2 – 150 kHz [10].

1.4 Operating challenges in sub-transmission networks

Even with RE generators certified to be fully grid code compliant, operational risks exists due to limitations of the grid code and due to external grid conditions such as network contingencies, weak grids and network resonance points. Opportunities to improve grid operations for both the NSP and the RE generator exist.

For any change to the grid code, there need be a requirement (trigger) and the technological advancement in order to implement the change.

The aim of this study is to:

- Identify the operational risks associated with utility scale introduction of RE generation in SA networks.
- Determine the impact it has on the South African NSP and the RE generators.
- Provide mitigating measures that can be taken by the Network service provider (NSP) with the current regulatory frame work.
- Recommendations to influence future South African grid codes.

1.5 Operational risks

Operational risks addressed in this research:

- Effect of voltage unbalance on RE generation operations especially during weak grid conditions.
- Ability of RE generators to stay connected to the grid during fault conditions.
- If supraharmonics exist and to what extent.
- Optimal use of reactive power when RE generators contributes zero active power required by specific network contingencies.

CHAPTER 2 LITERATURE REVIEW

2.1 Sources of renewable energy

Solar photo-voltaic and wind energy is a well-known renewable energy source and can be integrated in to the electrical grid by means of power electronics. Fundamental principles of both are briefly discussed next as context to the research.

2.1.1 PV generation

Solar radiation from the sun is converted to electrical energy (DC) by means of a photovoltaic device (solar panels). DC power is then converted into AC power in order to facilitate a grid connection. Power electronic switched are used inside the converters to synthesize a sinusoidal waveform. Isolated gate bipolar transistors (IGBT), switching at very high frequencies, are extensively used in modern converters [11].

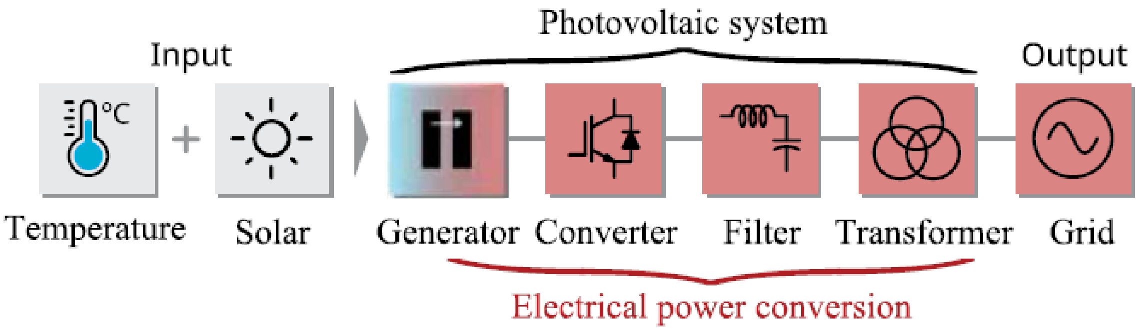

Figure 2-1: Typical PV system components, [12]

Depending on the connection voltage, generated power from the PV facility is stepped up with transformers to the appropriate voltage level. In large utility scale PV facilities, thousands of PV panels covering several hectares are connected to form a single facility with a HV or MV grid connection.

Fault level contribution of electronically connected renewable generation, such as inverter connected PV, is only equal to the rated current [11], [13] as energy is not stored by inertia in rotating mass and/or electro-magnetic fields.

2.1.2 Wind generation

A wind turbine converts kinetic energy from the wind into electrical energy as shown in Figure 2-2. Generation normally starts at wind speeds of 3-4 m/s, with rated power output at 11-12 m/s. Due to safety limits, wind turbines normally shut down at wind speeds in excess of 25 m/s.

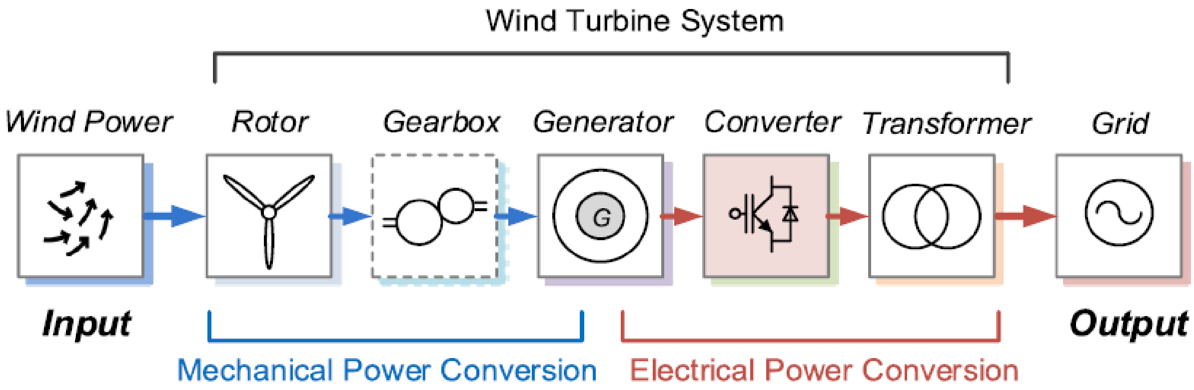

Figure 2-2: Wind power conversion [5]

First generation wind turbine designs were fixed speed wind turbines using an induction generator with a gearbox allowed the rotor speed to match system frequency. Variable speed turbines have increased efficiency by maintaining optimal power coefficient over variable wind speeds as rotor speed can be different to the synchronous speed required by the system frequency. To achieve that, the rotor is decoupled from the grid by means of power electronics that alleviate mechanical stresses [11].

Power electronics made it possible for the wind turbine to provide ancillary services to the electrical grid and thus variable speed generators became the standard for wind turbines worldwide. In South Africa, only variable speed turbines (type C and D) can comply with the grid code requirements in terms of reactive power support (being able to control active and reactive power independently) needed for voltage "ride-through" [11]. Only variable speed generators are considered in this research.

Double fed induction generators (DFIG) – also called type C or type 3 turbines and fully rated converter – also called type D or type 4 turbines are discussed.

2.1.2.1 Double fed induction generator (Type 3)

With a DFIG turbine, the generator torque is controlled with a power electronic converter as shown in Figure 2-3. The rotor is connected to a voltage source converter. Thus the voltage applied to the winding can vary in amplitude and frequency. The active and reactive power from the turbine can be controlled by manipulating the rotor currents. Since the rotor speed and system frequency is decoupled, the faster/slower rotation of the rotor is matched with the network frequency by injecting higher or lower frequency components unto the rotor as required. The power converter is usually 30% of the rated power of the wind turbine.

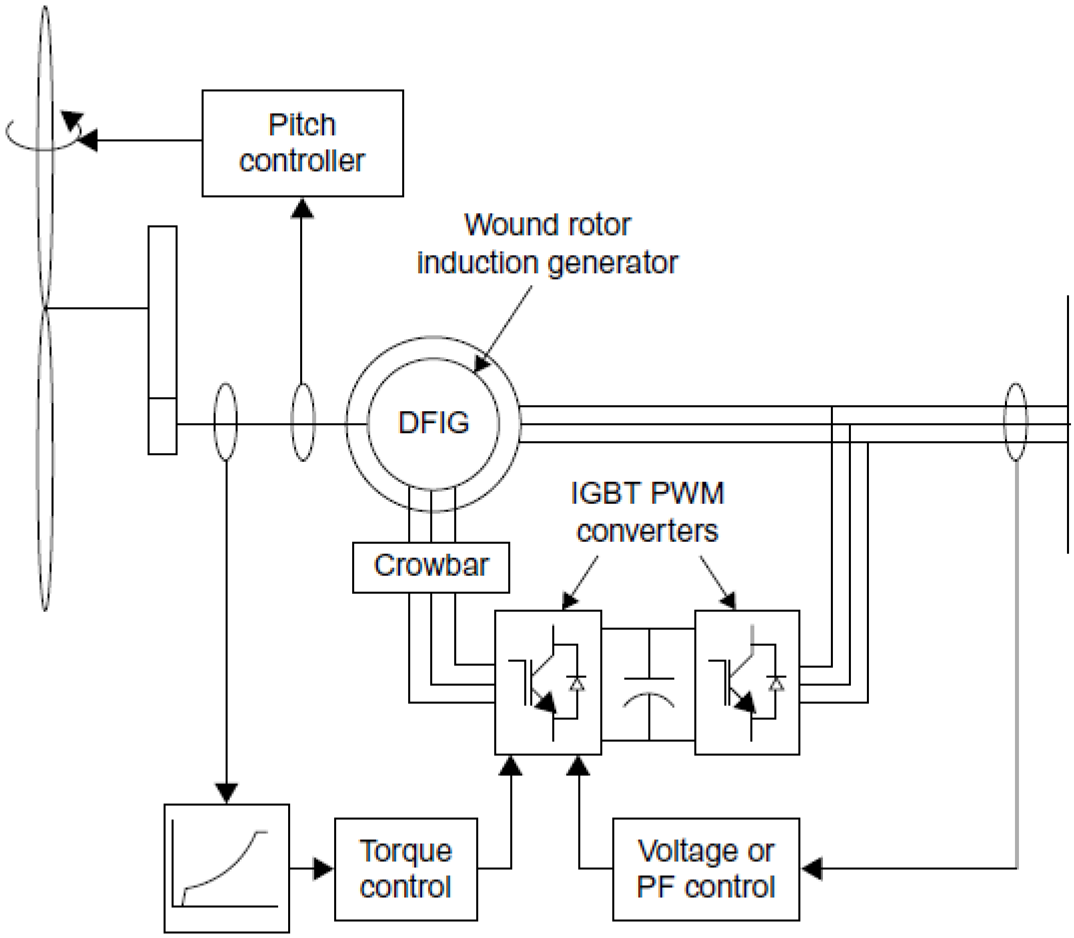

Figure 2-3: DFIG wind turbine, [11]

The structure of the power converter is two back to back two-level voltage source converters with common DC link. This allows for four quadrant power operation with low component counts, enabling a proven, reliable low cost turbine [5]. However, the use of slip rings contributes to lower reliability and inadequate control under fault conditions [14].

A DFIG wind turbine provides a transient fault current up to the limit of the rotor side converter. Crowbar protection, limits the amount of fault current delivered to the grid until disconnection [15].

2.1.2.2 Fully rated converter (Type 4)

In this configuration, a synchronous or induction generator is connected to the grid with a fully rated power electronic converter that converts the generated power (at variable frequency due to the variable speed of the wind and the turbine) to the value dictated by the grid frequency [11]. Two converters are needed as shown in Figure 2-4 making use of PWM switching transferring all of the generated power. The wind turbine-generator and the electrical grid are decoupled by the power electronic interface.

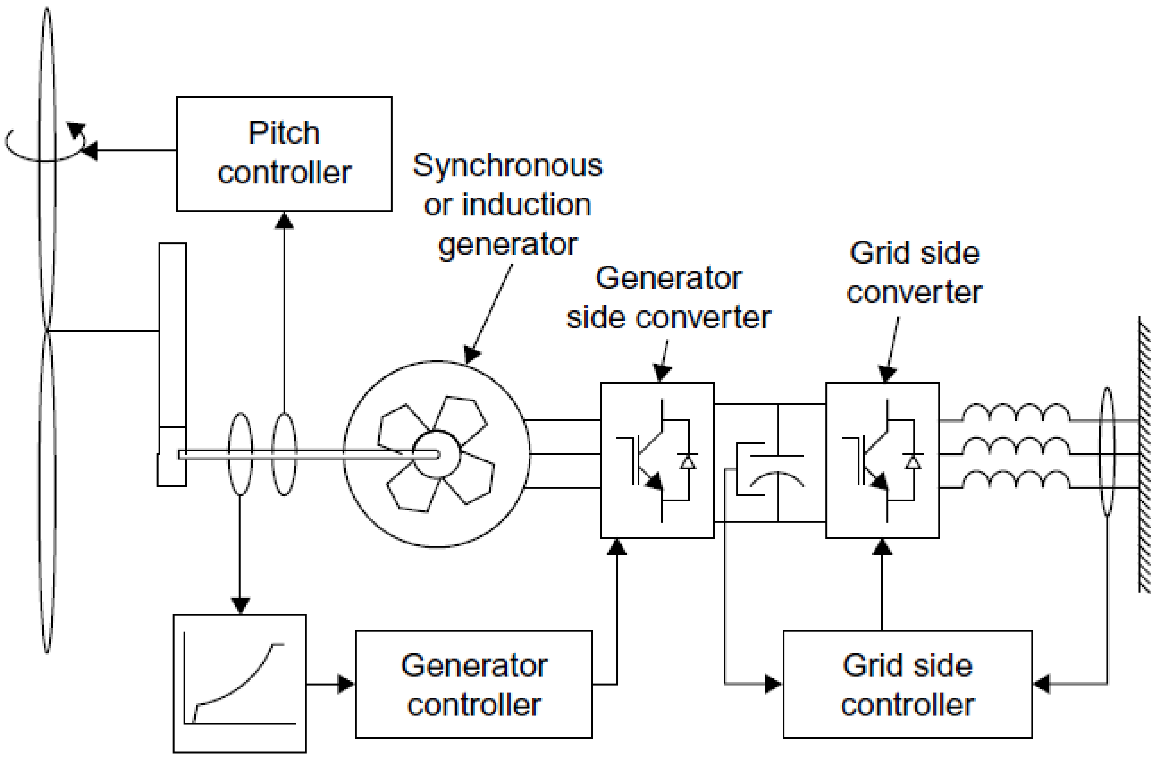

Figure 2-4: Type 4 wind turbine, [11]

Slip rings are eliminated when an induction generator is in use and a mechanical gearbox is simplified (or even removed with some manufacturers). This is the preferred configuration from a grid operator point of view as it enables improved control of reactive and active power. It is more expensive and less energy-efficient compared to DFIG technology.

Only the rated current of the power electronic interface of these type 4 wind turbines contribute to the fault level [11], [13] where they connect.

2.2 REIPPPP selection process

This section describes the process of connecting privately (independent from Eskom) owned RE generation to the grid. It describes the roles of all parties involved and discusses the technical requirements needed for a successful grid connection.

2.2.1 Overview of connection process

All RE generation under the DoE initiative is privately owned and classified as an independent power producer (IPP). Prospective RE generation developers apply for an indicative cost estimate (ICE) letter from Eskom via the grid access unit (GAU), reflecting the costs incurred by Eskom to connect an IPP to the Eskom grid. This GAU serves as a single point of contact in Eskom for the developer, from application to commercial operation

Cost estimate letters only considers the technical requirements for a grid connection and an estimated cost to facilitate a grid connection including:

- Multiple requests to connect at the same electrical node are considered individually.
- All commissioned or approved generation pertaining to the point of connection is taken into consideration.

- All technical criteria and limits are based on Eskom's Network and grid planning standard for generation grid connection [16].

Preferred bidders are selected by the DoE based on technical feasibility, cost of energy, local content, BEE ownership and job creation [1].

Once preferred bidder status is awarded, Eskom issues a budget quotation to the applicant. Most developers normally opt to design and construct the connection equipment (substation and lines) under the self-build agreement. The developer must appoint an Eskom approved consultant, contractor and an Eskom appointed clerk of works (COW). Designs have to be done according to Eskom standards and then approved by Eskom's technical evaluation forum (TEF). After Eskom has commissioned the apparatus, Eskom becomes the owner, operator and will maintain the connection equipment pertaining.

Preferred bidders sign the distribution customer use of system agreement (DCUOSA). This includes the operating procedures manual (OPM), which covers the relations during commercial operation between the DSO and the RE generator. The DCUOSA also includes limits apportioned for quality of supply, fault levels and scope of works. A PPA is signed between the SBO and the RE generator to cover the commercial operation of the plant.

2.2.2 Connection criteria

Technical considerations by the NSP on connection criteria when issuing an ICE letter, is discussed below.

2.2.2.1 Operating scenarios

Traditionally, network planning considered high and low loading scenarios. With the introduction of distributed RE generation, this expanded to include generation scenarios. The operating scenarios that are considered:

- High generation, high load (HGHL)
- High generation, low load (HGLL)
- Low generation, high load (LGHL)
- Low generation, low load (LGLL)

All operating scenarios are evaluated. The HGLL scenario is the most likely to cause an over-voltage condition. On sub-transmission and distribution networks, active power has a significant effect on voltage rise due to the low X/R ratio compared to transmission networks [16].

2.2.2.2 Thermal limits

The thermal limits of overhead conductors are determined by an Eskom standard [17]. Generation at the point of connection (PoC) may not exceed rate A of the thermal limit of the overhead line (OHL) or 100% of the grid transformer (if applicable) under normal network conditions. Rate B of the OHL loading is reserved for operational flexibility during network contingencies.

2.2.2.3 Voltage regulation

Within Eskom, different voltage limits exist for planning and operating. When planning for a new generator connection, the maximum allowed voltage regulation limit is 5 %. During operating under abnormal network conditions, the limit is relaxed to 7.5 % as shown in Table 2-1. A RE generator connected to the network may not cause voltage regulation exceedances. Reactive power capability of a plant can be used to lower the voltage at the PoC.

Table 2-1: HV voltage regulation [18]

Network state	HV voltage regulation
Normal	±5 %
Abnormal	±7.5 %

2.2.2.4 Rapid voltage change

Rapid voltage change (RVC), is defined as a sudden voltage change measured at the PoC. A rapid voltage change can occur due to:

- Disconnection of local load – this could cause a sudden increase in voltage.
- Sudden disconnection of the RE generator – this could cause a drop in voltage post fault.

The Eskom planning standard limits RVC to 5% for synchronous generating plant and to 3% for all other types for RE generators [16].

2.2.2.5 Fault level limits

Grid-connected distributed generation may not cause the fault level to exceed 80% of the rated fault level of any other equipment in this network. If the fault level does exceed 80% of the equipment rating, that equipment has to be replaced and this cost is added to the ICE letter.

2.2.2.6 Quality of supply

During the planning stage, the RE generator is not assessed on quality of supply parameters such as harmonics, flicker etc. Pre-connection quality of supply levels are shared with the developers, if available.

The impact of a RE source on quality of supply are described in the DCUOSA by means of apportioning emission values to a single RE source. Different sources of waveform distortion (flicker, harmonics, unbalance) will exist in an electrical network and because the owner of the network, Eskom in this case, has to contain the waveform distortion within the minimum technical standard used in SA for voltage quality, NRS 048 part 2-2015, each customer that connects to the a network has to be constrained in how much additional distortion is allowed in order for the network to remain well within the NRS 048 requirements.

IEC6100-3-2 [19] describes how to apportion distortion limits that may be contributed by any user of the network (such as the RE source) is described in the NRS 048 part 4Grid code compliance

Electrical networks were not designed for grid-connected renewable energy as it connects at points in the network designed for voltage drops and have an intermitted nature, injecting energy via non-linear solid-state interfaces. RE sources are also mostly owned by an IPP but cannot do business without the electrical network belonging to the NSP.

A grid code aims set the rules to which both has to obey, allowing the IPP to make money and the NSP to manage the electrical networks within technical standards and other operational requirements.

Minimum requirements to connect and operate safely with predictable behaviour during normal and abnormal network conditions are described for RE facilities [5], including advanced functions aiming to transfer some of the operational characteristics of conventional power plant such as rules on active and reactive power. This is referred to as providing ancillary services in addition to the selling of active power.

The requirements imposed on RE generators are categorized by the maximum export capacity (MEC) of the source at the PoC. These are set out in Table 2-2.

Table 2-2: RE generator categories

	MEC (MW)	Voltage level
Category A	P < 1 MW	LV only
Category B	1 ≤ P < 20 MW	MV or HV
Category C	P ≥ 20 MW	MV or HV

This section highlights key requirements RE generators needs to comply with to ensure grid code compliance in South Africa.

2.2.3 Governance

In order to ensure a uniform approach in connecting renewable generation in South Africa, NERSA (National Energy Regulator of South Africa) developed the first renewable grid code in 2010. Subsequently it has been revised to version 2.9, “Grid Connection Code for Renewable Power Plants (RPP) connected to the electricity Transmission System (TS) or the Distribution System (DS) in South Africa version 2.9” [20].

This grid code for renewables stipulates the minimum technical requirements for RE generators. All RE generators that connect to any South African transmission or distribution electricity network must comply with all the requirements stipulated in the code, unless a permanent or temporary exemption is granted by the GCAC (grid code advisory committee).

The CAC is tasked to compile and ament all grid codes as needed. Different role players participate such as Eskom, municipalities, industries and academics. Eskom System Operator acts as the grid code secretariat.

2.2.4 Compliance assessment

Compliance to the renewable grid code is evaluated by the Renewable Energy Technical Evaluation Committee (RETEC), consisting of members from Eskom, NERSA and municipal utilities. It is done from simulations and field data in conjunction with the Network service provider (NSP). Grid code compliance is a prerequisite to achieve commercial operation – the contracted date on which the RE generator may start selling energy to the grid. Compliance to the grid code refers to the entire facility and not individual units or turbines.

Assessment of grid code compliance has be done at the point of connection (PoC) agreed between the IPP and the NSP [20]. At the PoC, the IPP physically connects to the NSP. A PoC can be at an electrical node defined as being HV or MV as illustrated in Figure 2-5 and Figure 2-6.

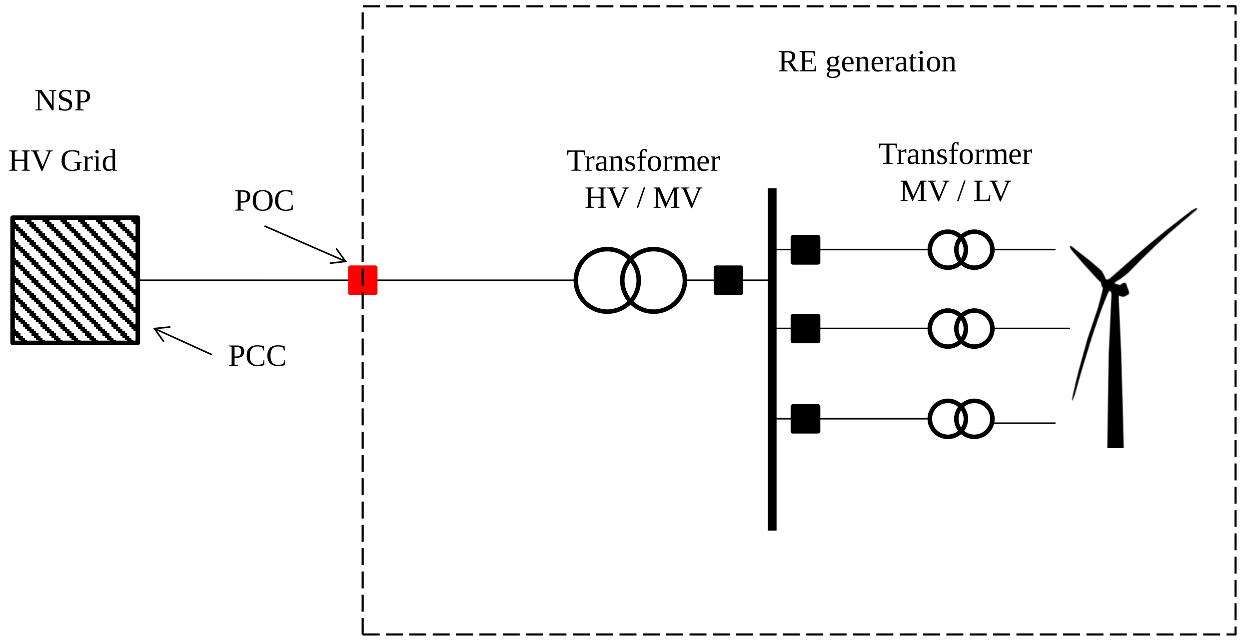

Figure 2-5: Typical layout of HV connected RPP

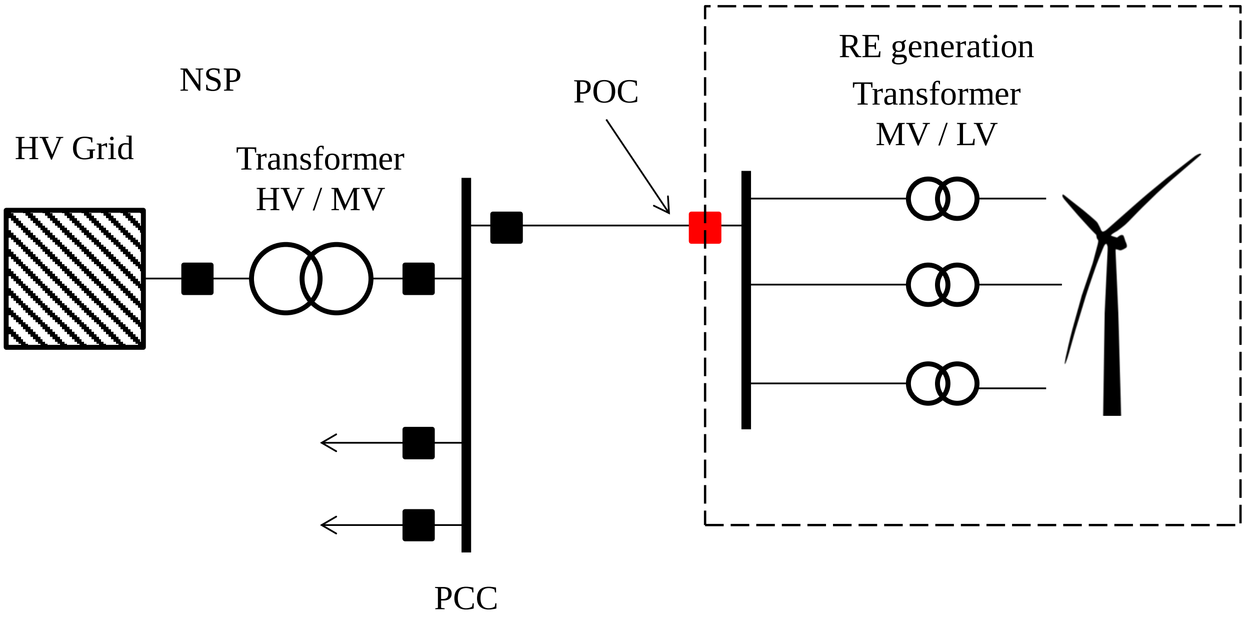

Figure 2-6: Typical layout of MV connected RPP

2.2.5 Active power control

RE generation is non-dispatchable in principle as the business goal of an IPP is to sell as much as possible electrical energy when the primary energy source (sun/wind) is available. Active power delivered into the PoC can be controlled by the DSO via the SCADA system, if needed to enable the DSO to meet system operational requirements of the interconnected power system overall.

2.2.5.1 Absolute production constraint

Active power *absolute production* constraint is a concept to constrain the active power at the PoC to a pre-set maximum value that can be delivered at the PoC. The delivered active power can be less, depending on the environmental conditions.

2.2.5.2 Delta production constraint

Delta production constraint is a concept to constrain the active power to a pre-set percentage of the potential active power output at the PoC to support the active power reserve needed for grid frequency control. For example, if the potential active power is 50 MW with a Delta production constraint of 5 %, the actual active power deliver at the PoC will be 47.5 MW, allowing the remaining 5 % to be available for frequency control. This is only applicable to wind and concentrated solar facilities [20].

2.2.5.3 Power Gradient production constraint

Power gradient constraint is the concept used to limit the active power up or down ramp rate to a pre-defined value, preventing sudden changes in active power output.

2.2.6 Reactive power capability

RE generation of category B and C are required to have leading and lagging reactive power capability related to their maximum active power output. Reactive power should be made available to be between 5% and 100% of rated active power output, with full reactive power capability available from 20% of active power production.

Reactive power capability curves for category C plants are in Figure 2-7 and summarized in Table 2-3.

Table 2-3: Reactive power capability of category B and C RE generators

	Power factor limits	Reactive power calculation	Example		
			Active Power	Reactive power (above 20 % active power)	Reactive power (below 5 % active power)
Category B	PF = ±0.975	$Q_{max} = 0.228 \times P_{max}$	15 MW	±3.42 MVAr	±0.75 MVAr
Category C	PF = ±0.95	$Q_{max} = 0.33 \times P_{max}$	100 MW	± 33 MVAr	±5 MVAr

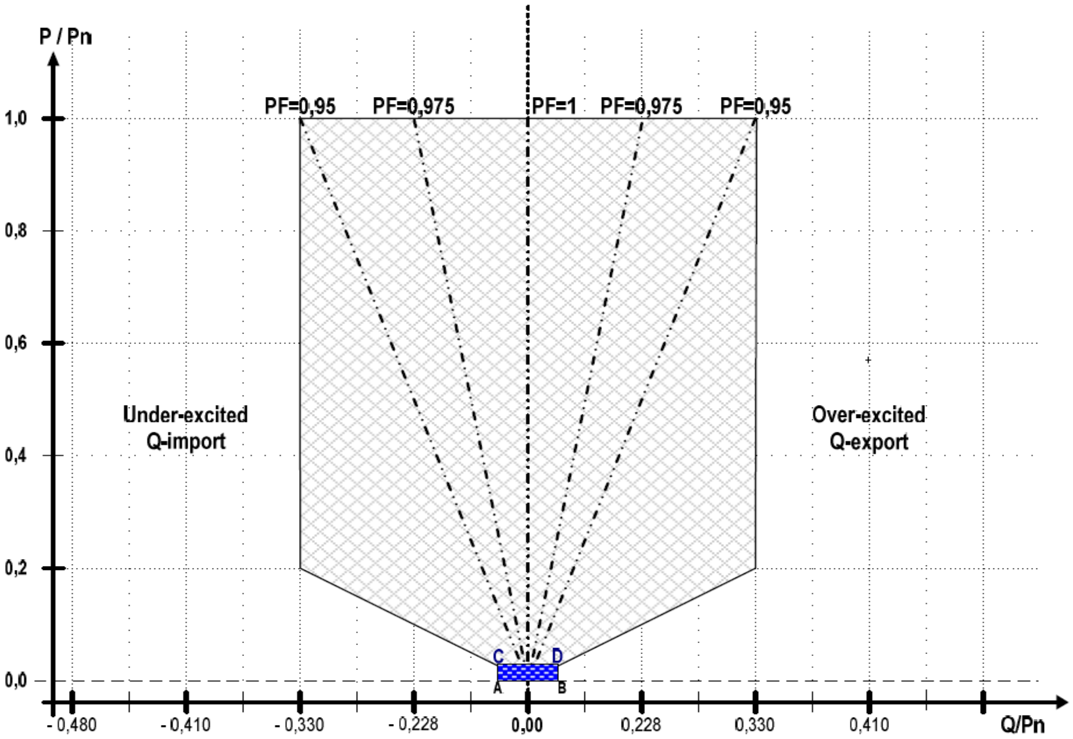

Figure 2-7: Reactive power requirements for category C RE generation [20]

At an active power output of less than 5%, no reactive power capability requirement applies. The plant should operate within area A-B-D-C (shown in Figure 2-7). No reactive power compensation is required during zero active power output, although it is possible for the latest generation wind turbines and inverters [8], [5].

Reactive power has to be controlled in one of three mutually exclusive modes, constant reactive power control, power factor control and voltage control, discussed next.

2.2.6.1 Constant reactive power (Q) control

Active and reactive power is controlled independently from each other. Reactive power is set as a fixed value either leading or lagging within the capability of the plant.

2.2.6.2 Power factor control

Reactive power production/absorption is controlled as a function of active power to keep the power factor at the PoC constant, either leading or lagging.

2.2.6.3 Voltage control

Reactive power production/adsorption is controlled as a function of the system voltage at the PoC, to regulate the system voltage. Control is performed with a droop setting. Figure 2-8 shows the operating point for two different droop settings.

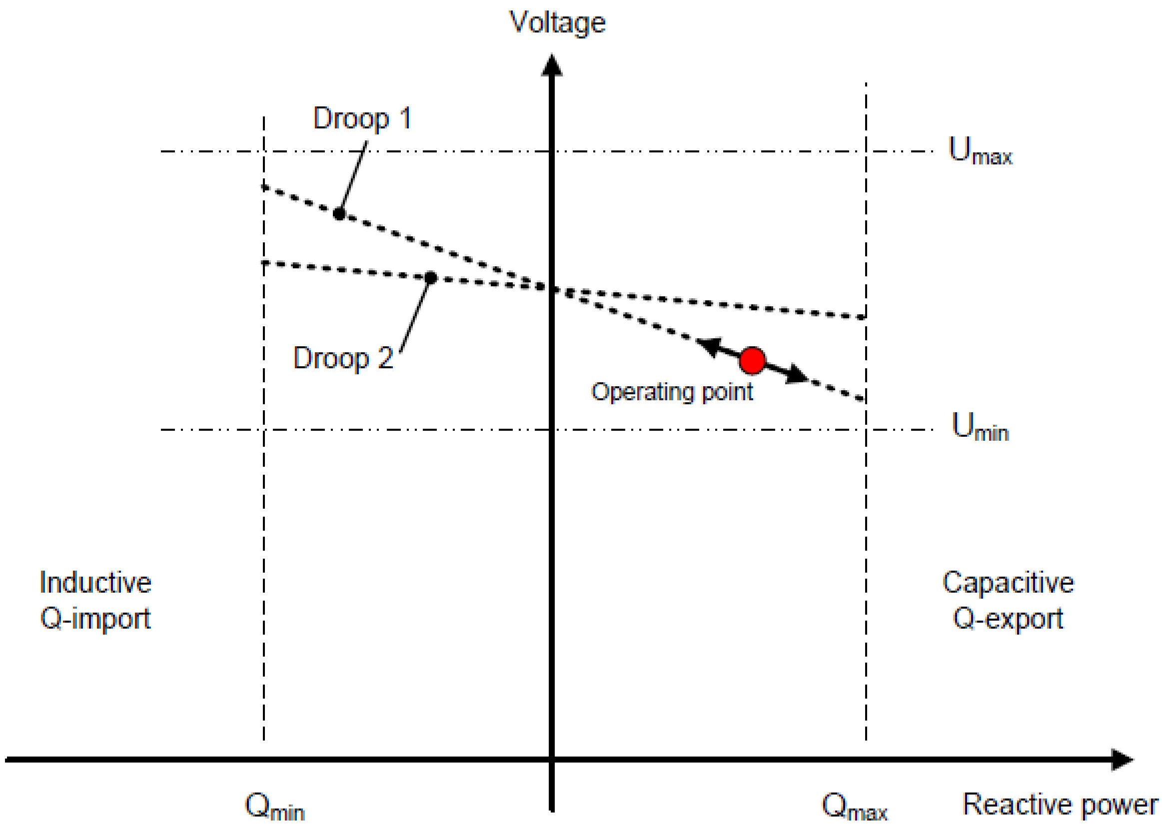

Figure 2-8: Droop based voltage control [20]

Droop settings cannot be changed remotely by the DSO via the SCADA system, like the voltage control set point.

2.2.7 Voltage ride through

Voltage ride through (VRT) refers to the ability of the RE generator to stay connected to the grid and provide reactive power support during the event in an attempt to stabilize the grid voltage. VRT criteria are applicable to all type of faults (symmetrical and asymmetrical). The bold line in Figure 2-9, represents the lowest voltage of all the phases for a low voltage ride through (LVRT) event or the highest voltage of all the phases for a high voltage ride through event (HVRT).

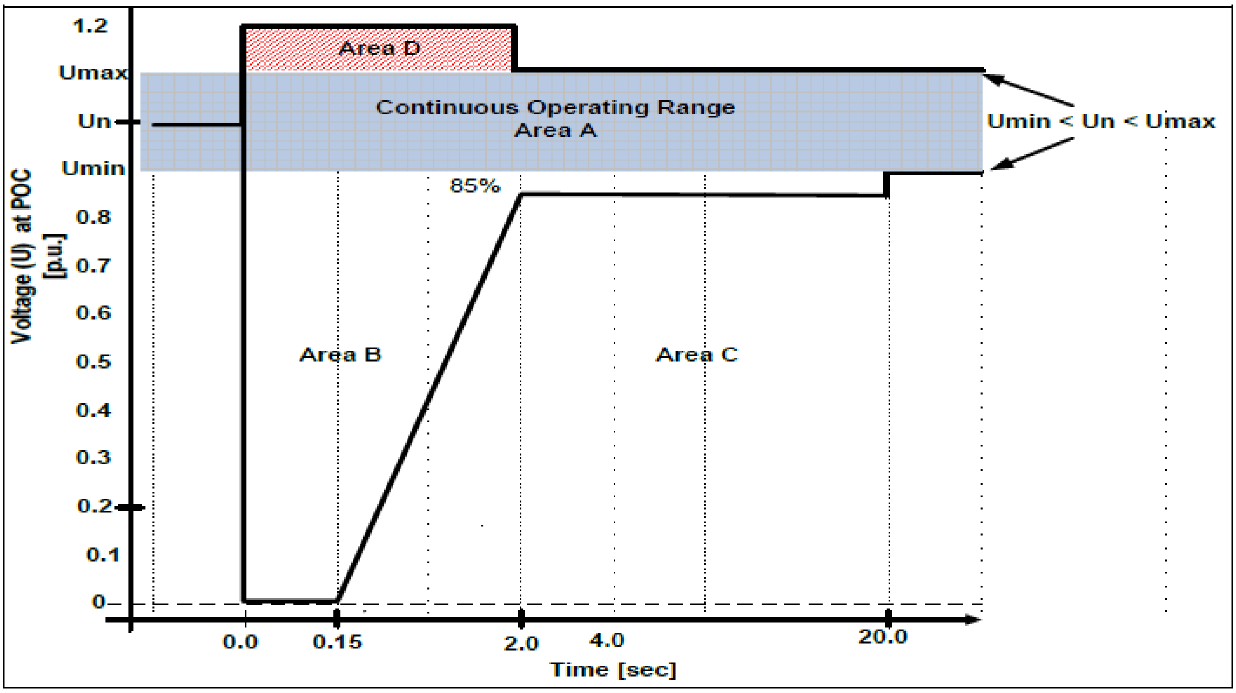

Figure 2-9: Voltage ride through capability for RE generators of category B and C [20]

Areas identified in Figure 2-9, also relates to those in Figure 2-10.

Area A – Normal operating conditions where the RE generation must stay connected to the grid and operated according to the active and reactive power set points determined by the DSO.

Area B – voltage dip. RE generation must stay connected to the grid and supply a controlled amount of reactive current to the grid in an effort to support the grid voltage. The required reactive current is shown in Figure 2-10

Area C – severe voltage dip. The RE generator may disconnect from the grid

Area D – over voltage. RE generation must stay connected to the grid and absorb a controlled amount of reactive current in order to reduce the voltage at the PoC. If the grid voltage is higher than 1.1 pu for longer than 2 s, or instantaneously higher than 1.2 pu, the generator may disconnect.

Reactive power support has priority over active power supplied in area B. Active power shall be sustained in area B, but a reduction in active power in proportion to the voltage dip (for dips below 85 %) is allowed. Once the fault is cleared, active power should restore to 90 % of the pre fault value within 1 s.

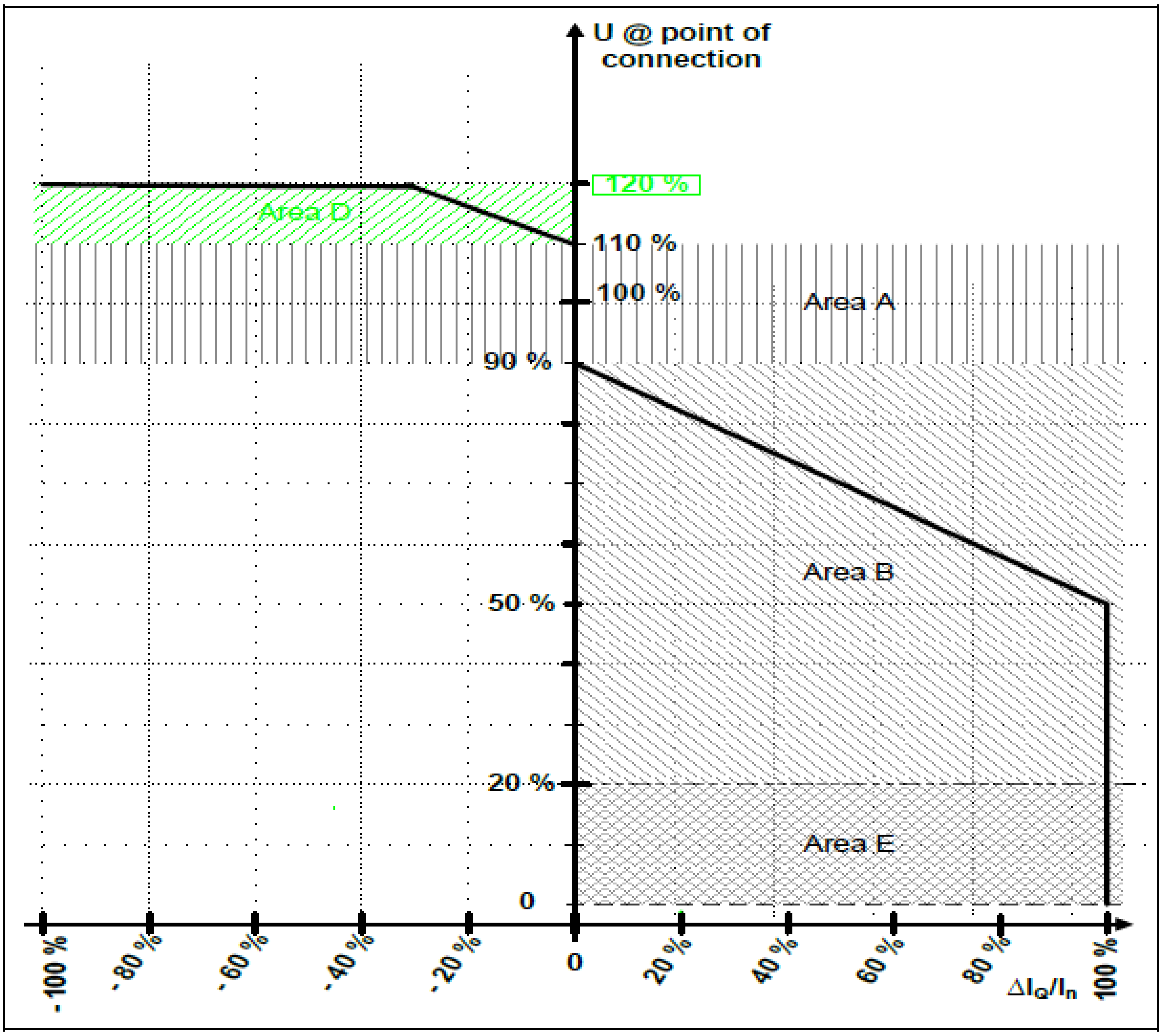

Figure 2-10: Reactive current supply during voltage events [20]

2.2.8 Frequency tolerance

Normal grid frequency in South Africa is 50 Hz. RE generators are allowed to disconnect from the grid under the following conditions as indicated in Figure 2-11:

- Grid frequency higher than 51.5 Hz for longer than 4 s
- Grid frequency lower than 47 Hz for longer than 200 ms
- Rate of change of frequency that is higher than 1.5 Hz/s

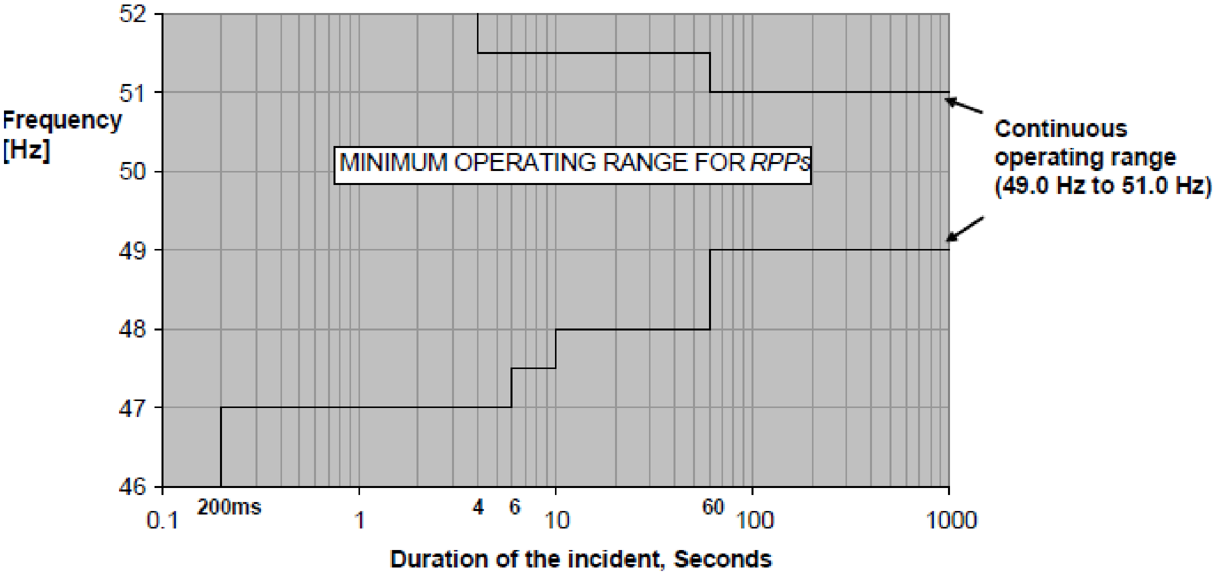

Figure 2-11: RE generation tolerance to frequency disturbances [20]

2.2.9 SCADA interface

Adequate and reliable SCADA interface between RE generators and DSO allows for seamless grid operation.

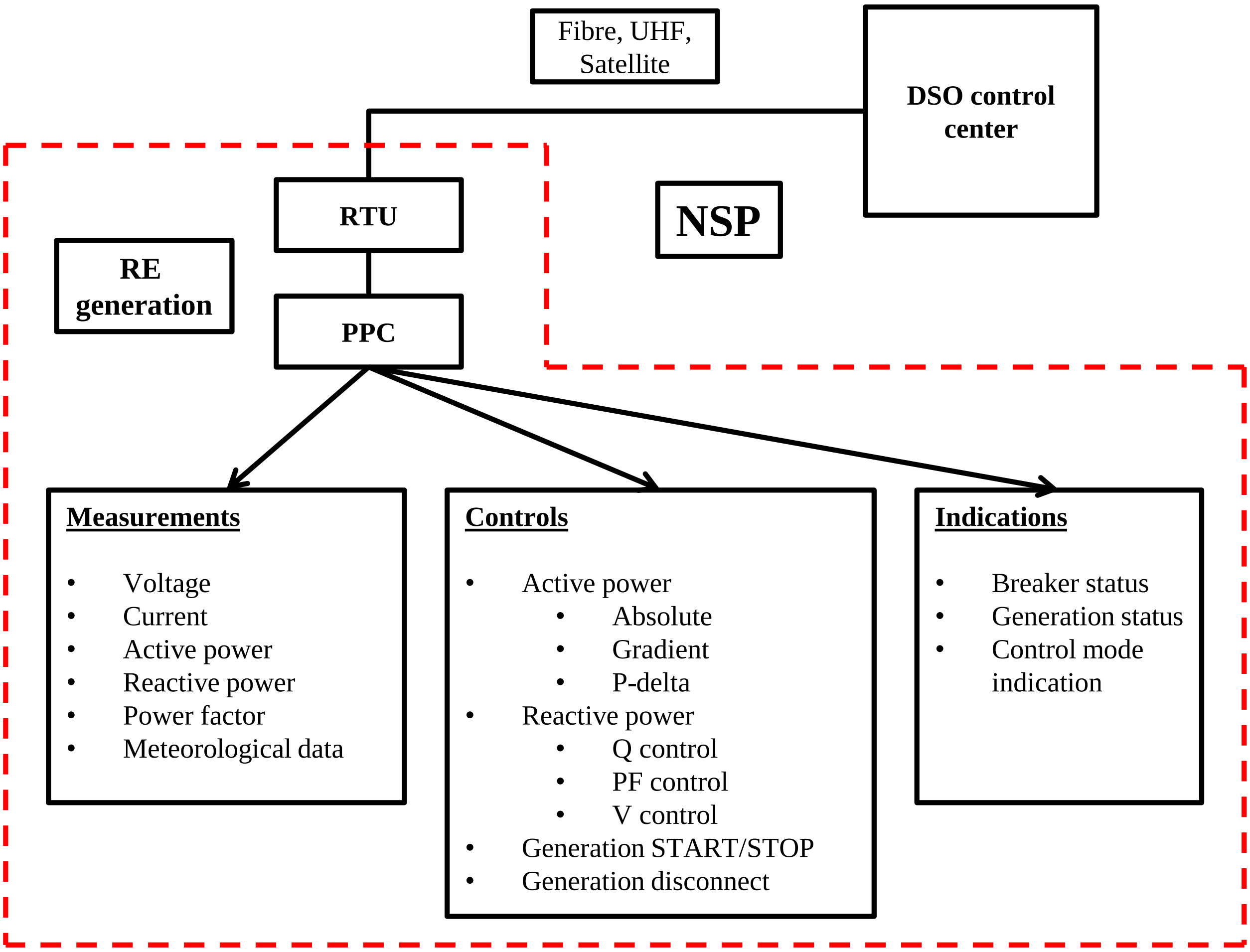

Figure 2-12: NSP – RE generation SCADA interface [21]

Eskom's interconnection [21] standard recommends the following SCADA communication interfaces (in this order): fibre connection, UHF radio communication (with cellular coverage as fail safe change over) or satellite connection (for remote areas with no communication infrastructure). The SCADA interface (shown in Figure 2-12) is divided into measurements, indications and controls.

2.2.10 Quality of supply compliance

Compliance assessment criteria for RE generation post commercial operation date (COD) include harmonics, voltage unbalance and voltage flicker based on the relevant apportionment limits. This apportioned values forms part of the DCUOSA and the RE source has to further proof once in production that those values are not exceeded (being "grid-compliant").

A RE facility is granted a 12 month temporary exemption after reaching commercial operation on all quality of supply compliance criteria in order to start monitoring quality of supply and then, if needed, implement solutions to contain emission to the apportioned values of the DCOUSA.

2.2.11 Summary

In the sections above show how the capabilities of RE generation evolved in order to operate in a complex grid. The role of grid codes was to facilitate this process and to mimic the response and behaviour of conventional generation in distributed renewable generation [5].

Renewable energy plants are now capable for regulating active power and frequency. Not only can the plants respond to frequency deviations, but it can assist in frequency control [5]. Reactive power can be controlled within a specific range in order to provide voltage support and counter act the voltage rise associated with increased generation.

In addition to support grid operations under normal operating conditions, distributed RE generators have the ability to respond to grid fault conditions. The development of low and high voltage ride through requirements became a standard practice in most of the grid codes [22] because the benefits associated with the functionality became undeniable [5]. Most recent grid code requirements in South Africa [20], Germany [23] and Denmark [24] do not only require the plant to withstand the voltage dip or swell, but require full reactive current support during the event to assist with voltage recovery.

The developments of these requirements consisted of two building blocks: there was a need to address a certain concern and there was technical advancement which unlocked the functionality needed to address the concern. In most cases the concerns were raised by TSO's or DSO's, whom foresaw the potential negative impact it could have on system operations. The technical advancement was enabled with the introduction of power electronics as seen in Figure 1-5.

2.3 Commercial aspects of RE generation

2.3.1 Overview of the electricity industry in South Africa

Eskom as a state owned company (SOC), is the responsibility of the Department of Public enterprises, but gets its mandate from the Department of Energy. NERSA (the regulator) regulates the electricity supply industry under the National Energy Regulator Act (Act no.40 of 2004). NERSA is also responsible of granting generation licenses, both to Eskom and IPPs. Eskom is responsible to facilitate the grid connection for IPPs based on preferred bidder status awarded by the IPP office (as part of the DoE).

2.3.1 REIPPPP Power purchase agreement

All IPP's (and in this case REIPP) sign a 20 year PPA with the SBO. It covers all the commercial aspects between the NPS and RE facility. RE generators are only paid for active power delivered at the PoC. Supplying or absorbing reactive power has no monetary value. Some of the applicable clauses of the PPA are discussed below.

2.3.2 Allowed grid unavailable period (AGUP)

Allowed grid unavailability period refers to the time period per year, a specific RE facility may be disconnected from the grid or the active power supplied at the PoC is limited by the DSO due to network constraints. The AGUP for transmission and distribution connected plants are set out in Table 2-4.

Table 2-4: AGUP for RPPs [25]

Connection voltage	AGUP
Transmission > 132kV	2% (175.2 h per year)
Sub-transmission and distribution	5% (438 h per year)

The following must be noted on AGUP:

- AGUP measurement is applicable even during periods of non-generation.
- If a facility is disconnected from the grid, due to network related incidents, the facility is allowed to claim grid unavailability. The claim will be evaluated by the SBO in conjunction with the relevant NSP.
- If the active power output of the facility is constrained downwards by the DSO due to local or upstream network constraints such as thermal or voltage violations, the facility is allowed to claim grid unavailability irrespective of the magnitude of the downward constraint.
- This is only applicable after the facility has reached commercial operation.
- Only after AGUP for a RE facility is exceeded, payment for deemed energy can be made.
- AGUP is accumulated during the financial year and resets to zero for the subsequent year.

An example of grid unavailability would be a planned or unplanned event on any equipment of the NSP that would cause an outage or partial active power constraint of the RE facility.

2.3.3 Deemed energy

Deemed energy refers to the potential energy that can be generated by a RE facility, but was not allowed by the relevant system operator. The RE facility is reimbursed for the potential energy that could have been delivered to the grid.

Deemed energy is paid under the following scenarios:

- RE generators are instructed to reduce generation output (curtailment) due to an over generation scenario. An example is excessive wind generation at night resulting in over frequency.
- Project delays by the NSP resulting in a delay in grid connection or commercial operation.
- AGUP has been exceeded for the financial year.

2.4 Network characteristics

This section describes the contribution of different network characteristics to voltage regulation on networks with distributed generation.

2.4.1 Voltage rise associated with distributed generation

Consider the example of the network indicated Figure 2-13. This will be used to define the concepts of short circuit power, short circuit ratio and the effect active and reactive power from the distributed generation has on grid voltage.

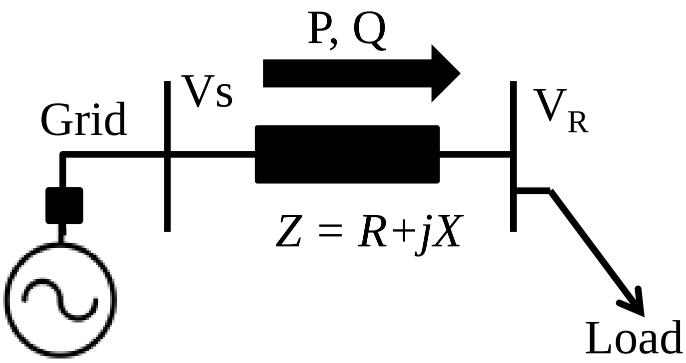

Figure 2-13: Simplified network layout

An approximation of the voltage drop on the network without any distributed generation is derived below [26].

$$\Delta V = \boldsymbol{V_S} - \boldsymbol{V_R} = \frac{RP + XQ}{\boldsymbol{V_S}} + j\frac{XP - RQ}{\boldsymbol{V_S}} \tag{1}$$

Only the real part of the voltage drop is considered because of the small angle between the sending and the receiving voltage. The sending bus is selected as the reference bus with voltage angle of zero, thus $\mathbf{V_S} = |\mathbf{V_S}| = V_S$. The equation can be rewritten as

$$\Delta V \approx \frac{RP + XQ}{V_S} \tag{2}$$

Selecting the sending voltage as the base voltage equation (5) can be written as

$$\Delta V \approx RP + XQ \tag{3}$$

ΔV: change in voltage (kV)

R: resistance (Ω)

X: reactance (Ω)

P: active power (MW)

Q: reactive power (MVAr)

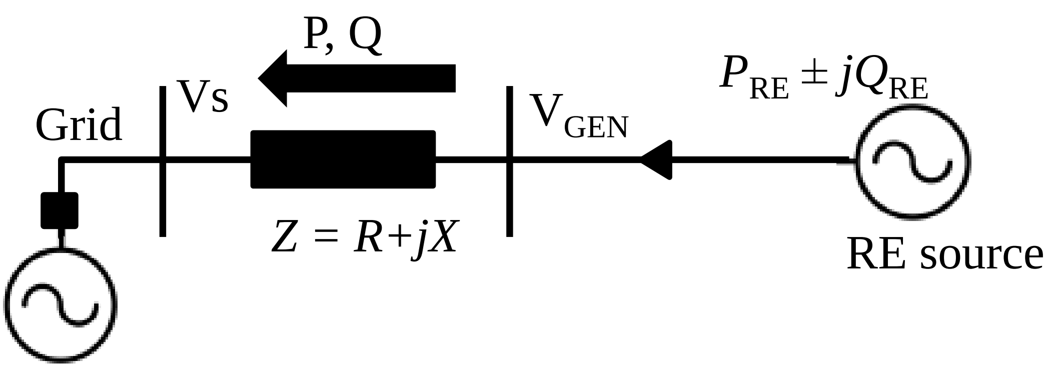

Figure 2-14: Simplified network layout with distributed generation

With connected renewables, the power flow is reversed. A voltage rise at the PoC is expected. Active power from the RE source is injected into the network. Reactive power can flow both ways depending on the reactive power set point of the RE generator.

Referring to Figure 2-14 the voltage rise attributed to RE generation is:

$$\Delta V \approx V_{GEN} - V_S \approx \frac{RP_{RE} + XQ_{RE}}{V_{GEN}} \tag{4}$$

V_{GEN}: voltage at PoC (kV)

P_{RE}: active power from RE source (MW)

Q_{RE}: reactive power RE source (MVAr)

From equation (4) is clear that the *X*/*R* ratio of the connecting network, with the active and reactive power of the RE source, has a substantial impact on grid voltage. An LV network, which has much higher resistance than reactance, will respond totally differently to HV and EHV networks.

Distributed generators will have a significantly different effect on the grid voltage depending on its size and connection voltage. Therefore, the voltage level also limits the amount of distributed generation that can be connected to the network at a specific point; this is not only a thermal limit, but also a voltage limit.

It is also evident from equation (1) that the active and reactive power has an influence grid voltage. When active power is at its maximum, there will be a voltage rise on the grid. Reactive power consumption of the distributed generator can lower the voltage rise attributed to active power injection

2.4.2 Fault level

Short circuit power (S_k) at the PoC of the distributed generation is calculated in [27] as:

$$S_k = \frac{V_S^2}{Z^*} \tag{5}$$

S_k: short circuit power (MVA)

V_S: voltage (kV)

Z: grid impedance (Ω)

Short circuit power (or fault level) is referred by field engineers as the “strength” of a network as the lower the impedance between the source and load (or distributed generation in this case), the higher the fault level as seen in equation (5) and such network regarded as “stronger”. As a network becomes “stronger”, the ability to contain voltage variations when current is changing, improves.

Short circuit power S_k affect voltage stability as shown in equation (6) below.

$$\boldsymbol{\Delta V = {}^{Q}/_{S_k}} \tag{6}$$

ΔV: change in voltage (kV)

Q: reactive power (MVAr)

From equation (6) it is clear that both fault level and the amount of reactive power injected or absorbed at a specific point on the network will have an impact on the grid voltage.

The lower the short circuit power, the bigger the impact of distributed generation on voltage regulation. Regulating grid voltages in networks with low short circuit power or in networks short circuit power can suddenly change, in is a challenge.

2.4.3 Weak networks

A weak network is regarded [27] as a network with high impedance (and therefore low fault short circuit power). Distributed generation could have a significant influence on voltage regulation.

A weak network is can be defined by assessment of short circuit ratio (SCR) [28] in equation (**7**)

$$\mathbf{SCR} = \frac{\boldsymbol{S_k at}\ \mathbf{PCC}}{|\boldsymbol{P_{DG}} + \boldsymbol{jQ_{DG}}|} \tag{7}$$

SCR: short circuit ratio

A network with a SCR of less than 10 is considered as “weak” [28].

Networks can be inherently weak based on their design by having relatively high impedances supporting energy flow. Reasons are:

- Networks with long lines suppling remote areas with very low loading.
- conductor used is barely sufficient in order to save cost

Network contingencies can result in an instantaneous change in short circuit power, adversely impact voltage regulation.

2.4.4 Power voltage curves

Power-voltage (PV) curves can be used to relate injected active power and the change in voltage at the PoC. In a sub-transmission network with relatively low X/R ratios (as compared to transmission networks), the active power contribution of a RE generator can have a significificate impact on voltage at the PoC.

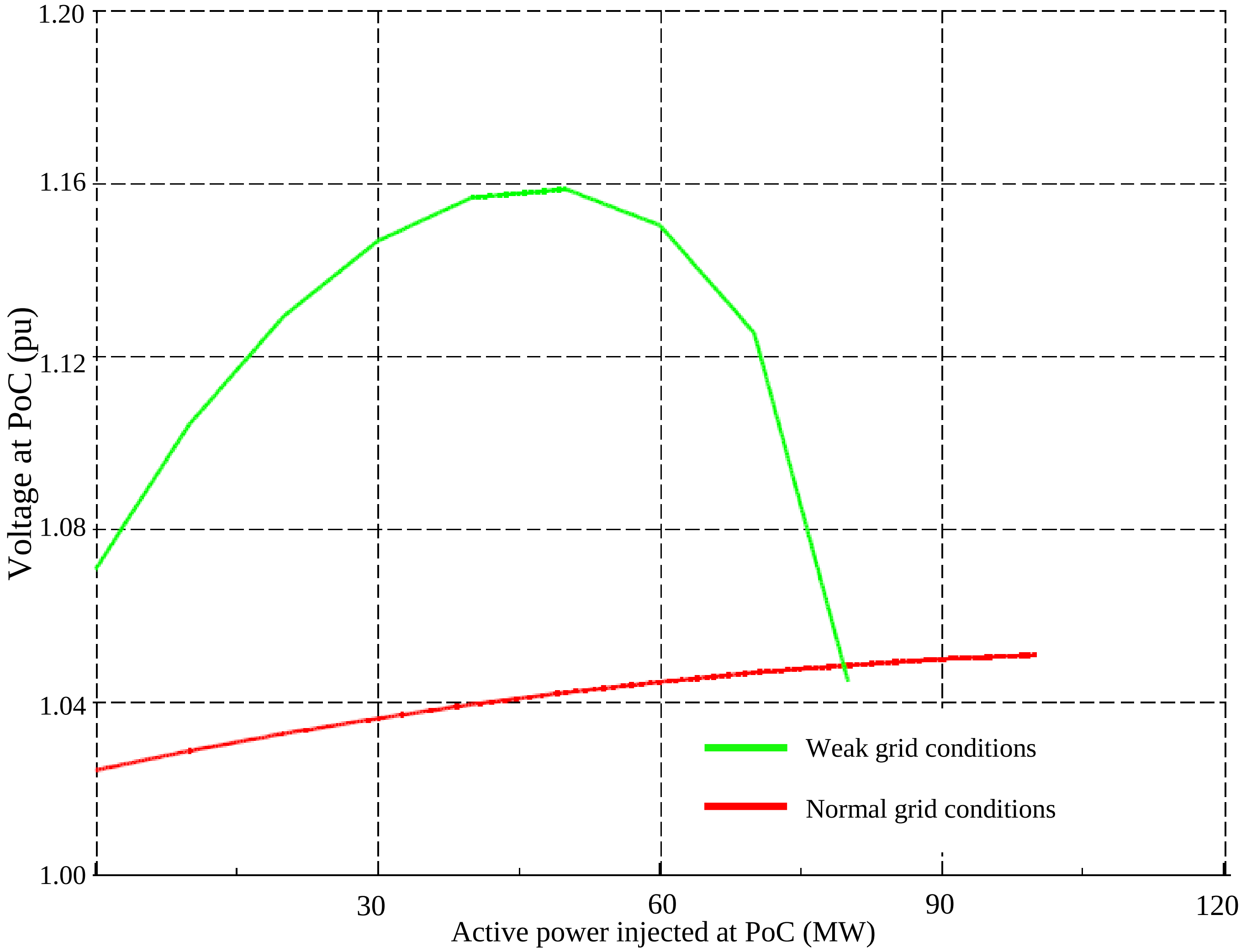

Figure 2-15: Power voltage curve for RE source injecting power into the grid

PV curve studies are usually performed under both normal and weak grid conditions. It is expected that the PoC voltage increase when the active power injection increase due to Ohm's law as shown in the red plot in Figure 2-15. The contrary can be realised as during high active power transfers across a sub-transmission line and under weak grid conditions, the reactive power consumption of the sub-transmission can increase substantially and lead to voltage collapse shown in the green plot in Figure 2-15.

2.5 Single phase AC traction networks

Single phase AC traction network are extensively used in South Africa and on some of these networks have been used as grid connections for RE generators.

2.5.1 Overview

Electrification of traction networks started in the 1840s with low voltage DC locomotives and supply [29]. As the need arose for longer and more powerful freight trains, AC supply systems became the technology of choice, due to more effective energy transfer over longer distances.

South Africa has an extensive long-haul rail network and featuring one of the longest railways in the world, the Sishen to Saldanha railway [29]. Energy is supplied from a 50 kV, 50 Hz (as suppose to a 25 kV network) due to the extreme length of the railway.

Other long distance freight rails use 25 kV, 50 Hz AC supply networks with substations approximately 30 km apart, next to the railway. Supply voltage of these traction networks are mostly at 275 kV, 132 kV or 88 kV.

Figure 2-16 shows a typical connection between the sub-transmission network (three-phase 132 kV, 50 Hz) and the traction supply network (single-phase, 25 kV, 50 Hz).

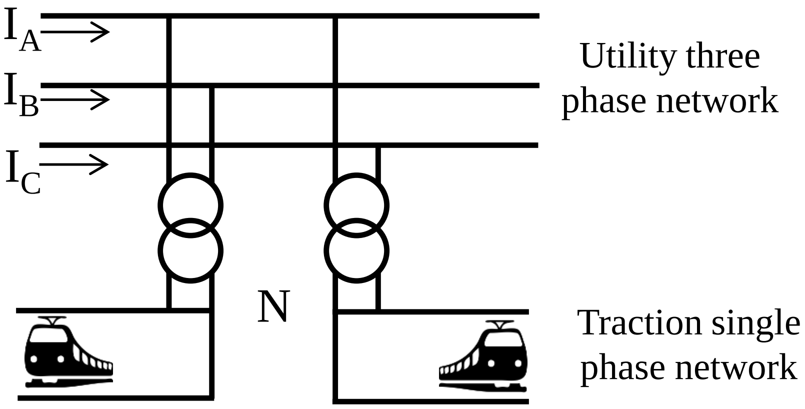

Figure 2-16: Typical sub-transmission – traction network connection

2.5.2 Problems associated with AC traction networks

AC traction networks cause some concerns to the upstream networks by:

- Harmonic distortion (caused by the converters on the locomotives)
- Voltage unbalance (single-phase traction loads)
- Poor network utilization (due to the intermitted nature of traction loading, there is a big discrepancy between mean and peak loads)

2.5.2.1 Voltage unbalance

Voltage unbalance in the upstream three-phase network is the result of single-phase traction loads withdrawing unbalanced three-phase currents. The pantograph connects to the overhead single-phase line transferring power to the locomotive. This phase-phase loading can be visualised by sequence domain components in Figure 2-17.

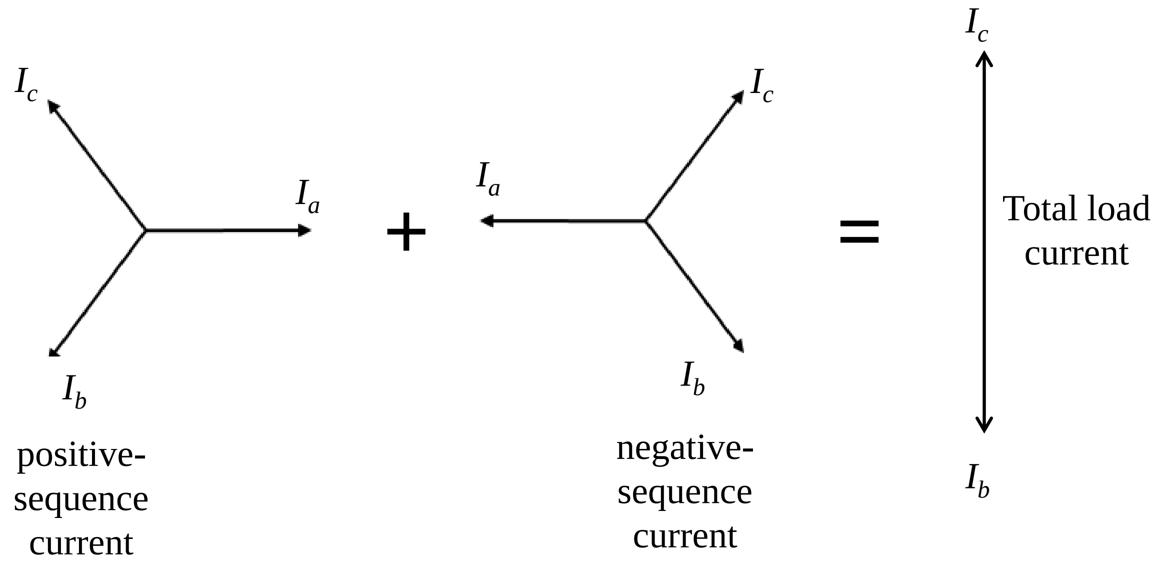

Figure 2-17: Phase sequence components for a single phase traction load

Single phase traction loads can be represented by phase sequence components as shown in Figure 2-17. Figure 2-17 shows a single phase traction load only connected between phase B and C. Current supplied by the upstream network consist of a positive and negative sequence component at 50 Hz.

2.6 Quality of supply

The quality of supply criteria listed below is not exhaustive, but relates to the operational risks associated with utility scale renewable generation.

2.6.1 Overview

Quality of supply refers to the quality of the voltage supplied by an electrical utility at the PoC to a customer. The minimum quality level, by which this voltage has to be supplied, is described in South Africa by the NRS 048 part 2-2015. This technical standard reflects international voltage quality standards. Local requirements are recognised for example by the manner in which voltage sags (dips) are classified and reported in Southern Africa.

When a customer withdraw current through a non-zero supply impedance, the voltage drop across that impedance affect the voltage quality at a PoC and a PCC. Voltage quality at any point in the network is therefore a reflection of the collective impact of each consumer of electricity and each supplier of electricity to this network.

Voltage quality is often referred to as power quality (PQ) and why standards documents mostly use the concept of PQ.

2.6.2 Power quality and distributed generation

The PQ of the upstream network can impact the performance of a renewable power source as shown in Figure 2-18. Similarly a renewable energy source can impact the PQ of the upstream network as shown in Figure 2-19.

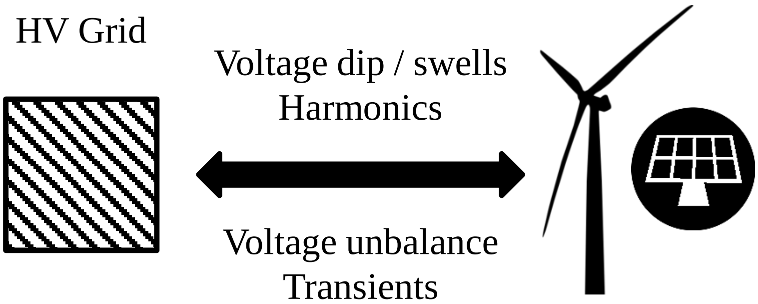

Figure 2-18: PQ in upstream network can affect distributed generation [30]

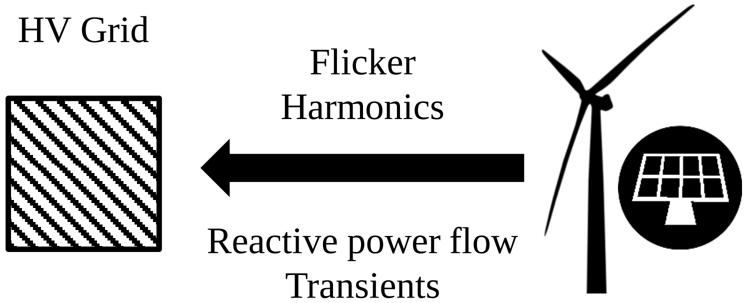

Figure 2-19: Distribution generation can affect PQ in upstream network [30]

Exceedance of PQ limits may lead to the disconnection of renewable energy source when the ability of the electrical utility is compromised to operate the network within the minimum levels of the technical standard (NRS 048 part 2-2015). For example, if it can be proven that the harmonic emission limits exceed the apportionment limits agreed in the DCUOSA and that this emission is from the RE source, then the RE generator must reduce the harmonic currents injected by installation of a harmonic filter.

To assess the contribution of harmonic currents by any single source of harmonics using single-point measurements is scientifically constrained, although widely perceived to be possible as shown in IEC6100-3-6 [31]

2.6.3 Measurement and compatibility

NRS 048-2 [32] requires a Class A power quality instrument to be used for the assessment of voltage quality. Emission of any PQ parameter is fundamentally based on current and for example described by harmonic current limits in the DCUOSA. This requires measurement of only those harmonic currents emanating from the renewable energy source. Network theory applied in an interconnected electrical network with sources of harmonic currents all over, has shown this to be not possible if measurements are not taken synchronously at all sources of harmonic currents in this network.

Compliance to the DCUOSA requirements have legal implications and for this reason, measurements used to assess this compliance, has to be obtained by an instrument that measures both voltage and current as stipulated by the international measuring standard for PQ, IEC 61000-4-30, edition 3 and on a Class A level.

The assessment period should be at a minimum seven continuous days that allow sufficient measurements during each power level required by the statistical power bins specified by the grid code for harmonics assessment. The power bins are used to present a varying generation profile over the generation period.

All three phase-earth voltages must be measured for solidly earthed systems as well as delta connected systems. The reference voltage shall be used for the assessment, except if declared voltage was agreed upon.

To assess compliance to the compatibility requirements of NRS 048 part 2-2015, IEC 61000-4-30 10 min aggregated PQ parameter values are needed. Only RMS values are retained and the loss of phasor information constrains root-cause analysis of emission.

Compatibility refers to those supply conditions where a specific parameter is not allowed to be exceeded for more than 5 % of the time during the measurement period. If a PQ parameter remains within the limit value stated for up to 95% of the total time of evaluation, then that PQ parameter is regarded as within the compatibility requirement and declared to be compliant to the NRS 048 part 2-2015 requirements.

2.6.4 Voltage regulation

Voltage regulation refers to the ability of the utility to maintain the supply voltage within agreed percentiles based on the nominal or declared (where applicable) voltages. With renewable connected to the grid, it introduces another mechanism which an influence the grid voltage. Irrespective of the connected RE generation, the NSP is still responsible to manage the voltage within the acceptable limits.

2.6.4.1 Compatibility levels for HV networks

10 min rms values are measured over a minimum period of 7 days. Compatibility levels for HV systems are 95 % for ± 5 % and 99 % for ± 10 % [32].

2.6.4.2 Voltage control

For voltage in the sub-transmission system, voltage regulation primarily is maintained by on-load tap changers (OLTC). Manually switched shunt capacitor banks are used to boost voltage during peak loading conditions. On transmission systems, in addition to OLTC, shunt reactors (inductors) are used to compensate the voltage rise. FACTS (flexible AC transmission) devices, such as SVC (static VAr compensation) and STATCOM (static synchronous compensator) are also used for voltage regulation

RE generation will increase the voltage at the PoC due to the active power injected as shown in section 2.4.1. The RE generation also has the ability to use its reactive power capability (section 2.2.6) to influence the voltage based on the reactive power control mode and set point.

Together with variable generation patterns and network contingencies, voltage regulation becomes challenging. It is therefore essential that the networks with renewables be studies under various conditions.

2.6.5 Voltage dips

The effect of voltage dips on RE generation is determined by the low voltage ride through (LVRT) criteria.

2.6.5.1 Definition

A voltage dip is defined as a voltage waveform event where rms voltage (on one or more phases) is suddenly decreased for a period between 20 ms and 3 s. This duration is measured from the moment voltage (in any one of the phases) sags below 0.9 pu of the nominal (or declared) voltage until the voltage recovers above 0.9 pu.

2.6.5.1 Causes of voltage dips

Voltage dips are mostly caused by faults in the network. Fault current into the short-circuit increase the voltage drops in all circuits towards the fault and it reflect at nodes remotely from the faulted point in the network as a reduction in voltage. At the fault, the voltage can be zero if the impedance of the fault is zero.

The residual voltage during the voltage dip is determined by the fault impedance between the point where the measurement is done and the fault location. If far away, the impedance will be more than when the fault is near, resulting in less reduction of the voltage at the measurement point. The duration of the voltage dip is determined by the type of protection system that clears the fault.

Overcurrent protection can take a few 100 ms, whilst HV protection on a definite inverse setting, can clear the fault in less than 100 ms.

Different duration and different residual voltage values can be recorded when observing voltage dips over a longer period of time and why the NRS 048 part 2-2015 classify each dip event according to a dip type as shown in [32].The DCUOSA document refers to dips not from this NRS 048 classification approach, but from a requirement set to “ride through capability”. It aims at defining the minimum conditions of a voltage sag where the renewable energy source has to remain connected to the electrical grid and is specified in the grid code, discussed in section 2.2.7.

2.6.6 Voltage swells

The effect voltage swells have on RE generation is defined by the high voltage ride through (HVRT) criteria. This will determine if the RE generation should disconnect or stay connected to the grid.

2.6.6.1 Definition

Over-voltage events are classified as voltage swells when the voltage in one or more phases increase with more than 10% of the nominal (or declared) voltage and for a period of between 20 ms and 3 s. When the voltage remain higher than 10% of nominal for longer than 3 S, then it is classified as an overvoltage condition.

2.6.6.2 Causes of voltage swells

Voltage swells can be the result of equipment being energised (switched) causing a sudden increase in reactive power being injected into the grid (i.e. capacitors). It can also be the result of lightning inducing transient charges into an overhead line.

2.6.6.3 Effects of voltage swells

Voltage swells can contribute to insulation breakdown, leading to increased failure of bushings and insulators.

2.6.1 Harmonics

Harmonics are multiples of the fundamental frequency superimposed onto the fundamental frequency sinusoidal waveform. Long term effects of exposure to harmonics mainly related to thermal effects on cables, transformers and motors.

2.6.1.1 Total harmonic distortion (THD)

THD is expressed mathematically as [32]:

$$THD = \sqrt{\sum_{h=2}^{n} V_h^2} \Big/ V_1 \tag{8}$$

n: highest harmonic order considered

V_h: percentage rms voltage of the h^{th} harmonic

NRS048-2:2015 recommends including harmonic orders up to the 40th harmonic.

2.6.1.2 Harmonic compatibility for HV and EHV networks

The compatibility levels for HV and EHV networks are shown in Table 2-5.

Table 2-5: Compatibility levels for HV and EHV networks

Harmonic order (h)	HV and EHV harmonic voltage (%)
3	2.5
5	3.0
7	2.5
11	1.7
13	1.7
17	1.2
19	1.2
23	0.8
25	0.8

The THD should not exceed 4 % when calculating harmonics up to the 40th harmonic order.

2.6.1.3 Derating of transformers

Transformers exposed to excessive harmonics might need to be de-rated due to the increase of transformer losses (heat) which could damage or reduce the life expectancy of the transformer. Losses are divided into Ohmic losses (I^2R) and additional losses (eddy and stray losses) [33].

Eddy losses at a particular harmonic are given by [33]

$$P_h = P_f \times r_h^2 \times h^2 \tag{9}$$

P_h: eddy losses at harmonic h (W)

P_f: eddy losses at the fundamental frequency f with the RMS of rated current I_r (W)

r_h: ratio of the magnitude of the current harmonic (h) over the fundamental current:

$$r_h = \frac{I_h}{I_1} \tag{10}$$

The total eddy losses are [33]:

$$P_{EL} = P_f \sum_{h=1}^{h=n} r_h^2 \times h^2 \quad (11)$$

The stray losses at harmonic order h is [33]:

$$SL_{ih} = r_h^2 \times h^{0.8} \quad (12)$$

The derating factor imposed on transformers exposed to excessive harmonics [33].

$$Derating\ factor = 1 - (\frac{Ttl}{Ttls})^{0.5} \quad (13)$$

Derating factor (pu)

Ttl: Transformer total losses at fundamental current (W)

Ttls: Transformer total losses with non-sinusoidal current (W)

2.6.2 Supraharmonics

Supraharmonics [34] refers to those high frequency harmonic components resulting from the switching operation within the solid-state equipment that interface sources of renewable energy to the electrical grid. This subject is new and why technical standards for limiting the impact onto the electrical network, is still under development. One concern is that power line communication can be compromised when supraharmonic frequencies between 2 kHz and 150 kHz are present in the networks.

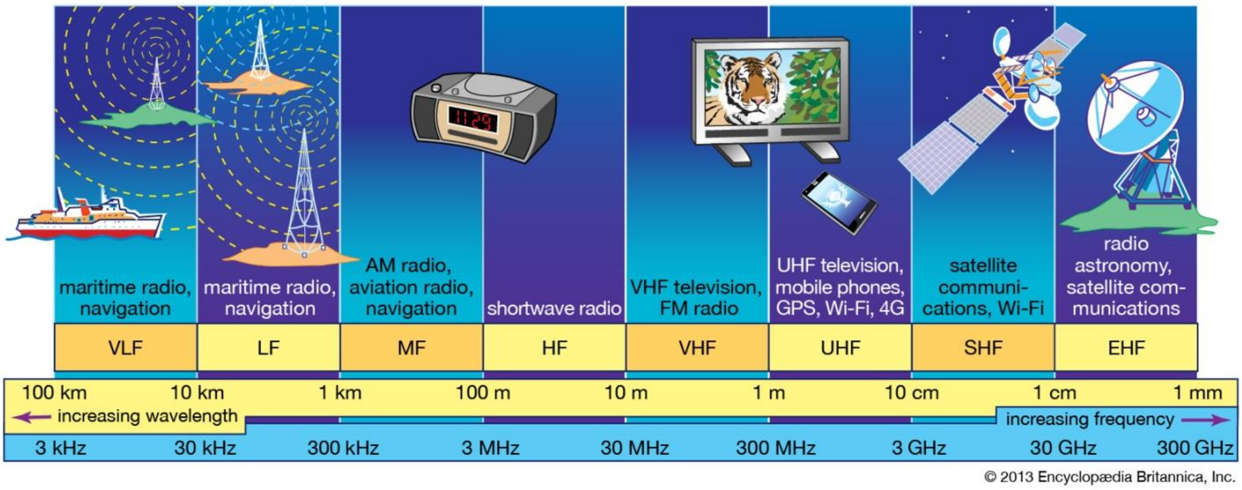

Figure 2-20: Radio frequency spectrum [35]

Figure 2-20 shows the commercially used radio-frequency spectrum. Supraharmonics emissions are at the lower end of the spectrum up to 150 kHz.

2.6.2.1 Source of supraharmonics

PV inverters are an important source of supraharmonic emissions [36]. The switching frequency in LV connected PV inverters are between 15 – 20 kHz whereas larger utility scale units are switching around 2 kHz [36].

2.6.2.2 Effects of supraharmonics

Some of the negative effects of supraharmonics are [10]:

- Failures in lamp dimmers
- Reduction in lifespan of LED lamps.
- Unreliable power line carrier (PLC) communication.
- Overheating of transformers and capacitor banks
- Failure of protection devices
- Transformers at RE facilities where supraharmonics exist might need to be de-rated due to the increased in losses. Eddy current losses increase with the square of the frequency [33].

2.6.3 Voltage unbalance

Voltage unbalance is one of the key problems associated with single phase AC traction networks. Connected renewable will also be exposed to the effects of voltage unbalance caused by single phase AC traction networks. Assessment of voltage unbalance and the problems associated with it is discussed.

2.6.3.1 Definition

Voltage asymmetry qualifies the unbalance in rms value of the fundamental frequency phase voltage phasors and/or asymmetrical phase displacement when the phase angle between the phasors is not perfectly 120^0 in a three-phase system.

From a mathematical point of view, it is expressed as voltage asymmetry. The ratio of the rms values of the negative to positive sequence voltage phasor at the fundamental frequency quantifies the negative sequence voltage asymmetry factor in a three-wire three-phase power system. Additionally in a four-wire three-phase power system, the ratio of the rms values of the zero to the positive sequence voltage phasor at the fundamental frequency quantifies the zero sequence voltage asymmetry factor.

The voltage asymmetry factor is then expressed in % as shown for the negative sequence asymmetry factor in equation (13) below.

$$UB = \frac{V_{\mathrm{n}}}{V_{\mathrm{p}}} \times 100 \tag{14}$$

UB: Percentage voltage unbalance in a three-phase three-wire power system at fundamental frequency

V_{n}: 50 Hz negative sequence voltage (V)

V_{p}: 50 Hz positive sequence voltage (V)

The compatibility requirement for networks operated at voltages up to 132 kV for voltage unbalance is to be less than 2% for 95% or more of the time. Contrary to PQ standards requiring that electrical loads have to perform as designed when subjected to a 2% voltage unbalance, the motor manufacturing association (NEMA) specify nameplate ratings to apply at 1.5% voltage unbalance, not 2% as “allowed” by PQ standards.

In networks with predominate single or dual phase supply, this value is relaxed to 3%. These networks are defined as:

- A network where the notified maximum demand (NMD) of the single and dual phase customers are more than 60% of the NMD for the feeder its connected to.

Or,

- The energy supplied to single phase loads is more than 60% of the total energy supplied during a 12-month period.

Or,

- A network where the actual maximum demand of the single and dual phase customers are more than 60% of the total maximum demand.

2.6.3.2 Causes of voltage unbalance

Voltages at a PCC becomes unbalanced when the loading is unbalanced resulting in unbalanced voltage drops over the supply impedances, even if those impedances between the upstream supply source and the PCC is perfectly symmetrical between phases. Typical configurations that cause this are:

- Single phase loads on three phase systems
- Unbalanced three phase loads
- Loss of phase on three phase system such as blown fuses or broken jumpers
- Temporary voltage unbalance can be caused by single phase faults

Even when loading is perfectly balanced between phase, voltage unbalance at the PCC can result when the supply impedances are not perfectly symmetrical such as due to un-transposed transmission lines.

2.6.3.3 Effects of voltage unbalance

Unbalanced phase voltages when applied to rotating loads such as induction motors cause a current asymmetry a factor of 6 – 8 times more due to the difference in negative sequence to positive sequence impedance of the motor. This negative sequence current can now be at least 12% of the positive sequence 50 Hz current assuming the voltage unbalance was 2%. A 12% negative sequence current cause a magnetic flux in the airgap of the motor opposite in direction to the magnetic flux resulting from the 50 Hz positive sequence current.

A reduced torque production results that increase the slip frequency of the motor when the torque requirements of the load remain the same as before. Due to the increase in slip frequency, the current into the motor will increase to increase the positive sequence current needed to generate additional positive sequence torque as needed by the load. This increase in rms current in the motor windings leads to an increase in I^2R losses that increase the temperature of the windings. If the thermal path of the motor cannot release this additional heat effectively, then the operating temperature of the motor increase and because winding insulation strength degrades significantly faster with temperature, the first winding failures can be expected much sooner.

In addition, the supply line losses increase (I^2R losses) and the apparent power loading of the system that increases, cannot be compensated by capacitors (improving power factor).

In most power electronic equipment, synchronization is needed to the fundamental frequency voltage waveform and if phase displacement exists, the operation of the power electronic equipment can be affected.

Muljadi et al [37] describes the effect of voltage unbalance has on induction generators such as used in older wind turbines. Uneven heating and hot spots in the windings resulted. Torque pulsations resulted in increased stress on the gearbox, additional noise and vibrations.

In South Africa power electronics interface the electricity grid to the wind turbine, mitigating the above concern.

The effects of voltage unbalance on specifically DFIGs have been well documented in [38], [30] and [39]. Small unbalanced grid voltages induced large unbalances in the rotor and stator currents leading to oscillations in electromagnetic torque [30]. Second order harmonics present in the electromagnetic torque can result in undesired oscillations [39] The excessive harmonics leads to increased losses and heating (resulting in insulation breakdown). The electromagnetic torque reduces the lifetime of moving parts (bearing, blades and gearbox) and emits noise.

2.6.3.4 Mitigation of voltage unbalance

Impedance in the supply system determine the magnitude of voltage unbalance and an approximation of voltage unbalance resulting from phase-phase traction loads can be based on fault level [40] as shown in equation (15) :

$$UB = \frac{P_{load}}{S_{SSC}} \tag{15}$$

UB = percentage voltage unbalance

P_{Load} – traction load (MW)

S_{SSC} – short circuit power (MVA)

Short circuit power can be increased in using additional (parallel) sub-transmission lines or supplying the traction load from a higher voltage [41], but expensive if not existing.

Inherent balancing in the traction system refers to alternating the phase connection on traction supply substations. For example, the first substation will be connected between the red and white phase and the next section between white and blue phase, next between blue and red, repeating this sequence over the whole line.

Since there is no cost involved, it is most commonly used in South Africa. Unfortunately, it is also the least effective option as it cannot minimize the instantaneous voltage unbalance at a specific point along the traction line.

Local balancing using transformer connections by a number of different transformer connection arrangements have been developed for traction electrification. These include Scott, Woodbridge and LeBlanc connection transformers that represent the single-phase traction load as a three phase load to the three-phase upstream network.

Local balancing works best in passenger rail systems with high throughput of trains since two trains on opposite sections can balance out the energy requirements of the single-phase loads by balancing the energy in the three-phase supply system. This approach becomes much less effective with long haul rail systems since there isn't enough traffic on the rail to balance the energy requirements.

External balancing consisting of voltage source converters (VSC) such as SVCs or STATCOM devices are considered an effective solution to continuously mitigate voltage unbalance even under weak grid conditions.

[40] describes the application and benefits of using VSCs to mitigate voltage unbalance. The VSC has the ability to control the voltage in amplitude, phase and frequency independently.

A 3-level voltage source converter (VSC) with PWM modulation shown in Figure 2-21. By switching the DC voltage of the capacitor with IGBTs, a sinusoidal-like waveform can be achieved. Phases (a, b, c) can either be connected to the positive side of the capacitor or negative side of the capacitor or midway resulting in 3 possible switching states.

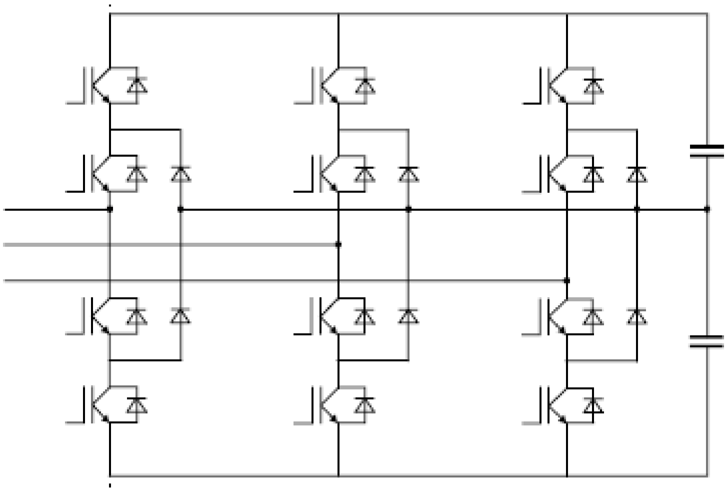

Figure 2-21: 3 level voltage source converter [40]

For the VSC to balance the load current, it injects pure negative phase sequence current into the system. The pure negative phase sequence current is directly out of phase negative phase sequence component of the total traction load current as shown in Figure 2-17. The result is a seemingly balanced load current as see in Figure 2-22.

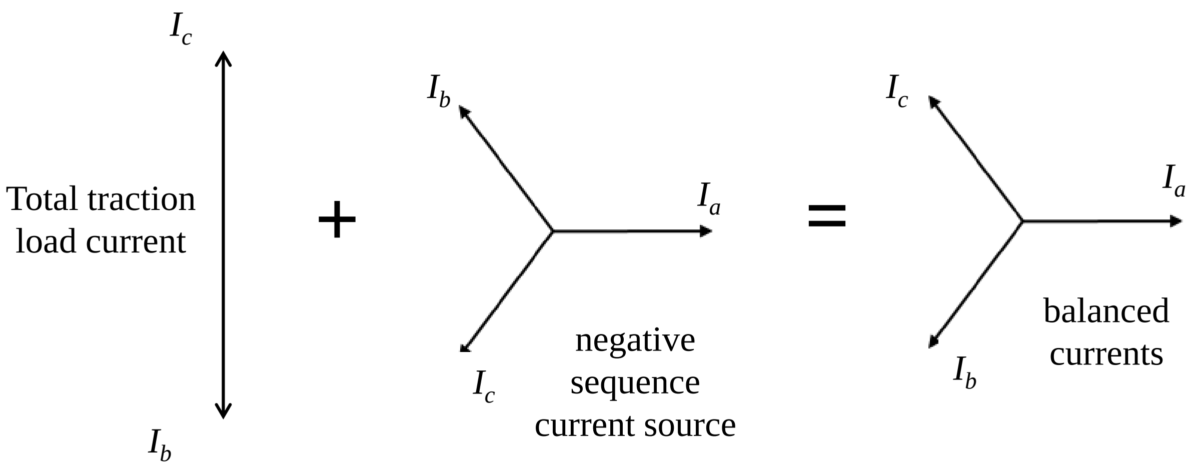

Figure 2-22: negative sequence current source [40]

In a case study in France, under weakened network conditions, the maximum voltage unbalance was 7%. With the implementation of a STATCOM, maximum voltage unbalance reduced to 1.5% under weakened network conditions [42].

2.6.4 Compensation of voltage unbalance using RE generators

Since power electronics forms such an integral part of RE generators, the concept is to use the embedded power electronics to compensate for voltage unbalance. Two methods are described below.

2.6.4.1 Balancing stator currents

Most of the control strategies focused on minimizing the adverse effects of voltage unbalance on the generator [38].This only reduces the effect of the voltage unbalance on the generator and does not eliminate the voltage unbalance in the system. Generators are thus more robust and able to withstand the effect of voltage unbalance has on the generators, but are unable to rectify the voltage unbalance in the system.

An induction generator exposed to unbalanced grid voltage will exhibit highly unbalanced stator currents which leads to torque pulsations at twice the grid frequency [43]. This can lead to damage to the gearbox, rotor shaft or blades.

Reducing in electromagnetic pulsations can be achieved by using a controller capable of stator-voltage-oriented *dq* vector control [43]. From the results in [43], the compensating controller is able to reduce the second order harmonic torque and reactive power pulsations and the stator-current unbalance. In order to achieve this, the rotor converter must also be rated higher due to an increase in rotor voltage [43].

The improved control scheme allows the generator to tolerate much higher levels of grid voltage unbalance as well as decreasing the mechanical wear on equipment [43].

2.6.4.2 Injection of negative phase sequence current

Since power electronic converters are already present in DFIGs, it can be used to compensate for voltage unbalance as the power electronics are capable of injecting negative phase sequence current [38]. In [44] the authors propose to use the power electronic converters in the DFIG to inject negative phase sequence current into the AC system.

Various methods are described to use either the rotor side or grid side converter to achieve this with the objection of reducing the voltage unbalance at the PCC [38]. The current carrying capacity of the converters limits the amount of control that can be achieved. Normally the converter in a DFIG turbine can only transfer about 30 % of the total generated power.

The advantage of this scheme is that it does not require any hardware upgrade, but it requires and substantial increase in processing power.

2.7 Conclusion

Implementation of grid code requirements on RE generators have led to increased cost of renewable technology due to the incorporation of advanced technologies, but results in renewable power more suitable for grid integration [5]. Technical demands of the grid code for the connection of RE plants were enabled by power electronics.

Ancillary services like voltage and frequency support under normal grid conditions and voltage ride through during fault conditions made renewable energy more acceptable and enable further grid penetration. This was driven by the demands from the TSO/DSO and implemented through widespread adoption of the grid codes.

As seen from the discussion above, RE generators go through various approval processes before permission is granted to connected to the grid. After grid connection, the RE generator must pass grid code compliance. RE generators that passed all the requirements, might under specific network conditions exhibit operational risks.

CHAPTER 3 OPERATIONAL RISKS

This chapter discusses the identified operational risks associated with utility scale RE generation on sub-transmission networks. All operational risks are based on a network / RE generation combination currently in operation. The RE generators complied with all the network requirements and grid code regulations, yet operational risks exist.

3.1 Renewable generation under voltage unbalanced conditions

RE generation sources are in SA often located in remote areas (due to availability of wind, solar irradiation and space) and connected to networks susceptible to weak grid conditions and voltage unbalance [30], [38]. In this research the integration of RE sources is addressed where voltage unbalance is a concern due to single phase AC traction loads sharing the same networks

3.1.1 RE generation connected to traction networks

Significant RE generation in SA injects to networks where traction networks are regarded as the main concern to voltage quality. For the purpose of the research reported in this document, the list of RE generators that are already connected to traction networks (within the control area of Bloemfontein DSO) are listed in Table 3-1 and shown in Figure 3-1.

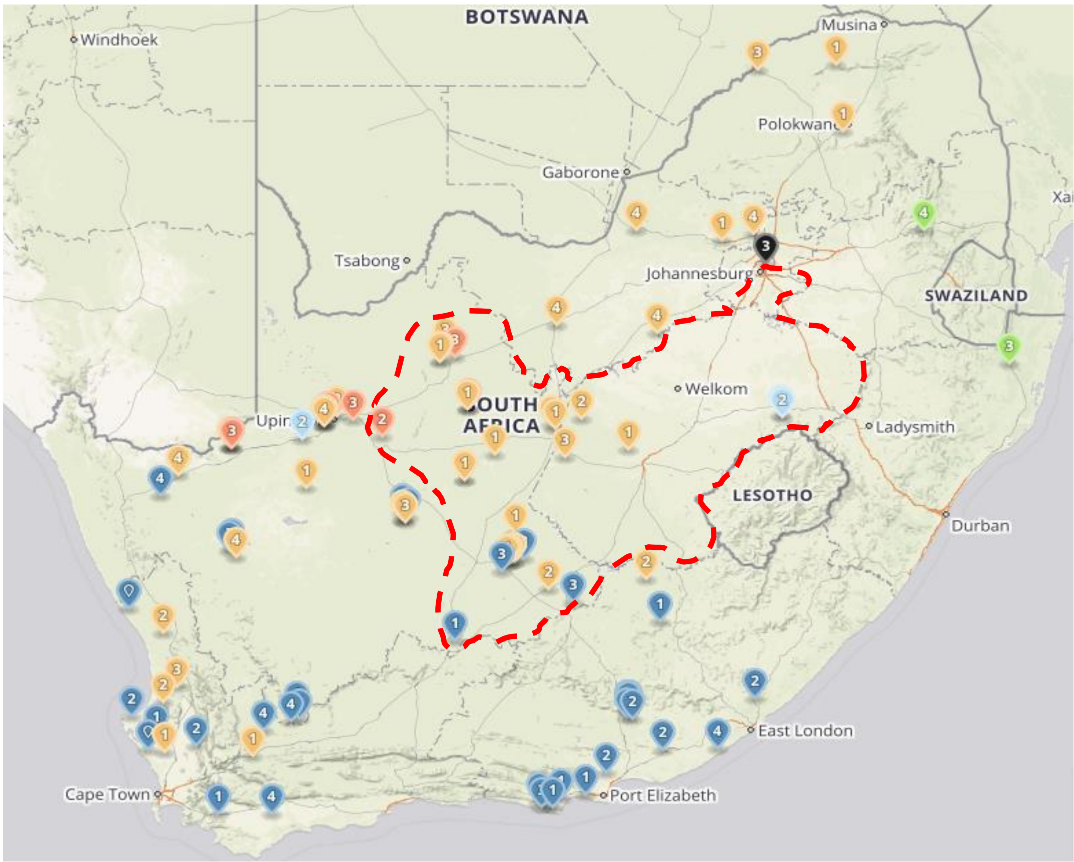

Figure 3-1: Distribution of RE generation in South Africa

Table 3-1: Renewable energy projects on sub-transmission traction networks

No.	Plant Name	Type	Size	Voltage level	Network
1	Noupoort	Wind	80 MW	132kV	Hydra – Poseidon
2	Linde	PV	36 MW	132kV	Hydra – Poseidon
3	Bokpoort	CSP	50 MW	132kV	Garona
4	Kalkbult	PV	75 MW	132kV	Hydra – KDS
5	SCDA1	PV	75 MW	132kV	Hydra – KDS
6	SCDA3	PV	75 MW	132kV	Hydra – KDS
7	De Aar Solar	PV	48 MW	132kV	Hydra – KDS
8	Lesedi	PV	64 MW	132kV	Olien – Ferrum
9	Sishen Solar	PV	75 MW	132kV	Ferrum – Hotazel
10	Droogfontein	PV	45 MW	132kV	KDS – Ulco
11	Noblesfontein	Wind	75 MW	132kV	Hydra – Droogfontein
12	Jasper Solar	PV	75 MW	132kV	Silverstreams - Manganore

Operational risk resulting from these RE sources are analysed next with the goal to contain it within the constraints of the technology in use by the utility and the RE installations

3.1.2 Operational risk

Traction networks are notorious for having poor quality of supply, specifically voltage unbalance and harmonics [45]. RE generators are not designed to withstand high levels of voltage unbalance. Some local wind turbines, supplied by Siemens, claims that they can only tolerate 2% voltage unbalance [46].

Under weak grid conditions, voltage unbalance can increase significantly. RE generators connected to sub-transmission traction networks may disconnect when voltage unbalance increase beyond 2%.

From Eskom field data, it was noted that when voltage unbalance increase, voltage harmonics increase. In [47] it is shown that triplen harmonics generated in wind turbines can be transferred to the network, even over a delta-star winding transformer if the wind turbine is connected to unbalanced loads.

Assuming that the supply network is “delivering” this voltage unbalance, the RE source’s compliance to the DCUOSA limits is compromised. Non-compliance requires forensic analysis of system conditions of Eskom.

3.2 Voltage ride through

Compliance to voltage ride-through is beneficial to both the RE generator operator and the NSP. Remaining connected during an upstream fault results in no loss in revenue for the RE generator operator and no effect on the system frequency. The effect on system frequency may be accentuated in areas with a large amount of RE generators in close proximity.

3.2.1 RE generation clusters

Even though the total generation contribution from RE in SA is comparatively low (see section 1.1), local generation clusters formed near main transmission stations (MTS). Clusters of RE sources are the result of low cost connection options on offer by the NSP due to network capacity, availability of wind or sun and physical space for turbines or PV panels.

As an example, the total renewable generation feeding into Hydra MTS on 132 kV has a potential of 712 MW. The generation consisting of 10 projects (4 wind farms with the potential to generate a total of 390 MW and 6 PV farms with a total of 322 MW) shown in Figure 3-2.

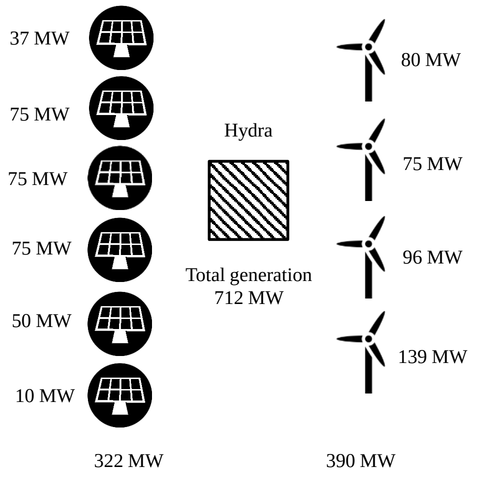

Figure 3-2: RE generation cluster at Hydra

During a fault on the transmission network, all RE sources connected to the MTS (such as at Hydra) would experience a voltage dip. Should the majority of the connected RE generators disconnect during this fault, it will result in a significate generation loss, to the extent that it will affect system frequency.

If frequency is not successfully contained by the national control centre, both RE generation and Eskom generation will disconnect resulting in a system blackout condition. Such scenario is not only an operational risk to Eskom, but it is a national strategic risk to the whole country.

For this reason, the ability of RE sources to fully comply to dip ride-through incidents are strategically important and even more important as a whole during a clustering situation such as at Hydra MTS.

3.2.2 Compliance testing of voltage ride through

Grid code compliance testing for voltage ride through is only simulation-based in South Africa. It will usually be an optimistic representation of the RE source network model, and the test results are fully dependent on the effective functionality of that model.

Low voltage and high voltage ride through scenarios are simulated with the voltage dip (or swell) reference back to the PoC. For example, should there be a fault in the upstream network, a dip could realise at the PoC for a specific RE facility. All individual units must collectively contribute to "ride-through" the voltage dip as shown in Figure 3-3.

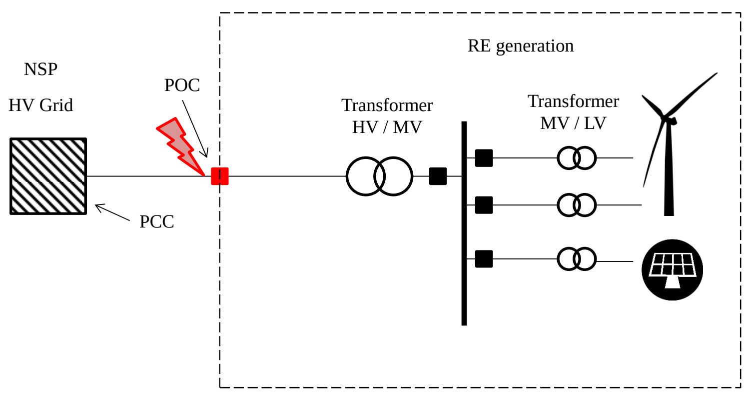

Figure 3-3: Typical HV grid connection in South Africa

Models supplied by the RE facility developers are usually simplified versions as the details of the control systems are regarded as proprietary information. Lack of detail information can result in different performance during simulation studies and in real-life conditions, making the prediction of plant performance unreliable and simulation studies insufficient. Using these models creates an operational risk to the electrical utility and business risk to RE source operator.

EU countries define the PoC at the MV terminals of the individual generating units shown in Figure 3-4. RE sources have to respond individually to voltage events, in contrast to that of SA. Compliance of individual RE generators in the EU are validated at independent specialist laboratories during a process known as “unit certification”. RE facility developers can select RE generator from manufacturers based on a certification process that validates performance. Application for grid connection is now based on the type of certification applicable to the RE generator used at the facility.

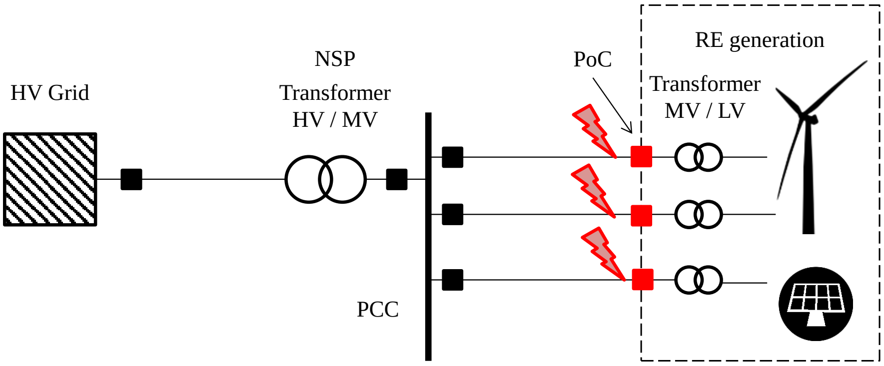

Figure 3-4: Typical HV grid connection in EU

3.2.3 Case studies

Due to the increase of number and size of RE facilities within grids, LVRT requirements have become standard in most grid codes [48]. LVRT is seen as very important especially in areas with high local penetration levels. Not complying with the LVRT requirement can lead to an amplification of the event. As multiple units trip, the frequency does not recover and leads to even more units tripping.

On 24 February 2011, 274 wind turbines in 10 wind farms tripped in Jiuquan, China (Gansu province) due to a lack of LVRT functionality [49]. Network frequency declined from 50.034 Hz to 49.854 Hz. The wind turbines which disconnected equals 54.4 % of the total wind generation near Jiuquan.

3.2.4 Risk

Compliance to voltage ride is though is not tested in South Africa, but only simulated, the risk is that RE generators are not compliant to the requirements and the NSP does not have any method of determining compliance. As seen above, non-compliance to voltage ride through could have a severe impact on the entire power system.

3.3 Supraharmonics

Power electronics is the enabler for more advanced control and functionality of RE generation. Being inherently non-linear and switching high currents at high frequencies, the same power electronics are also responsible for the concern on higher order harmonics resulting from those switching frequencies, supraharmonics [10].

3.3.1 Limitations of regulation

RE generation plants are not assessed with regards to supraharmonics as there aren't any limits or assessment criteria for supraharmonics in South Africa. International standards are in development. Work group C4.24 is a joint working group between CIRED and CIGRE with a specific mandate to define the scope for frequency components between 2 – 150 kHz [50].

CIGRE working group C4/C6.29 – "Power-quality aspects of solar power" is also looking into the subject of supraharmonics.

3.3.2 Limitations of measurement

The NSP won't even be aware of supraharmonic emissions in the network, since there aren't any dedicated recorders installed that can measure supraharmonics. The devices installed at present (used for compliance reporting to the regulator) are not configured to effectively measure supraharmonics. Special requirements to the sampling speed are needed to measure frequency components up to 150 kHz.

3.3.3 Risk

At present there aren't any regulations in South Africa to measure, report or set compliance limits for supraharmonics. Correct measuring of supraharmonics is the first challenge in order to determine the long-term effects on HV apparatus when exposed to supraharmonics.

The frequency band between 9 – 148.5 kHz is used for power line communication (PLC). This is in the exact range of supraharmonic emissions and might cause interference [51].

3.4 Reactive power support during zero active power output

Providing reactive power support during active power generation is a well-established requirement in RE grid codes. It is required that RE generators in South Africa generating 20 MW or more, has the ability to operate at a leading or lagging power factor of 0.95.

3.4.1 Need

Under normal network conditions, reactive power compensation is used to contain the voltage increase resulting from active power injection in to the grid. Voltage increase as this flow of active energy is against the "normal" flow of energy and this grid was designed for voltage drops in order to serve voltage to consumers of energy at an acceptable voltage level, remote from a PCC. Injecting energy is against the design/operation philosophy and why voltage can be increased.

Under weak grid conditions, the grid may provide adequate reactive power support to sustain voltage under peak loading conditions. The RE generator can support the grid voltage by contributing for reactive- and active power.

RE generation levels are set by the local weather (irradiation, wind). Active power support cannot be guaranteed. As all PV and wind generators in SA interface to the grid with power electronics, reactive power support is possible regardless of weather during weak grid conditions.

3.4.2 Implementation

From a utility perspective to realise reactive power support from RE sources, the following aspects requires consideration:

- RE generators must be able to contribute reactive power during zero active power output.
- This functionality is not needed everywhere in the network and the NSP has to include this requirement from RE sources where it is needed in the electrical grid.

- Detail of how the reactive power support has to be realised must be included in the operating agreement.
- A commercial agreement is needed for ancillary services supplied by RE sources.

3.4.3 Potential benefits for the electrical utility

The benefits are:

- Increased operational flexibility: network contingencies that were problematic can now be handled without exceeding the voltage regulation limits.
- Delayed capital investment: contracted RE facilities can provide reactive power support needed during weak grid conditions, helping the NSP to delay capital projects.

3.4.4 Potential risks to the electrical utility

Voltage control is not under the full control of the NSP as a privatised user of the distribution grid now also contributes. The NSP cannot control how well maintenance is done of the RE equipment and is a risk that can affect the availability of reactive power when needed by the NSP.

CHAPTER 4 VERIFICATION

The operational risks identified in chapter 3 are further investigated in this chapter. Various networks (associated with the different operational risks) are modelled and simulated under different network conditions to determine the impact the risks.

4.1 Renewable generation connected sub-transmission traction networks

Single phase AC traction networks are a source of voltage unbalance. Connected RE generators are susceptible to the voltage unbalance caused by the traction networks. The effect voltage unbalance, especially under weak grid conditions, will have on connected renewable will be simulated based on a real world scenario consisting of a PV and wind facility.

4.1.1 Network layout and description

A 132 kV sub-transmission network (build between Hydra and Poseidon) is shown in Figure 4-1 and Figure 4-2. The network was built for the establishment of the rail infrastructure. Figure 4-2 shows the 132 kV network adjacent to the rail road.

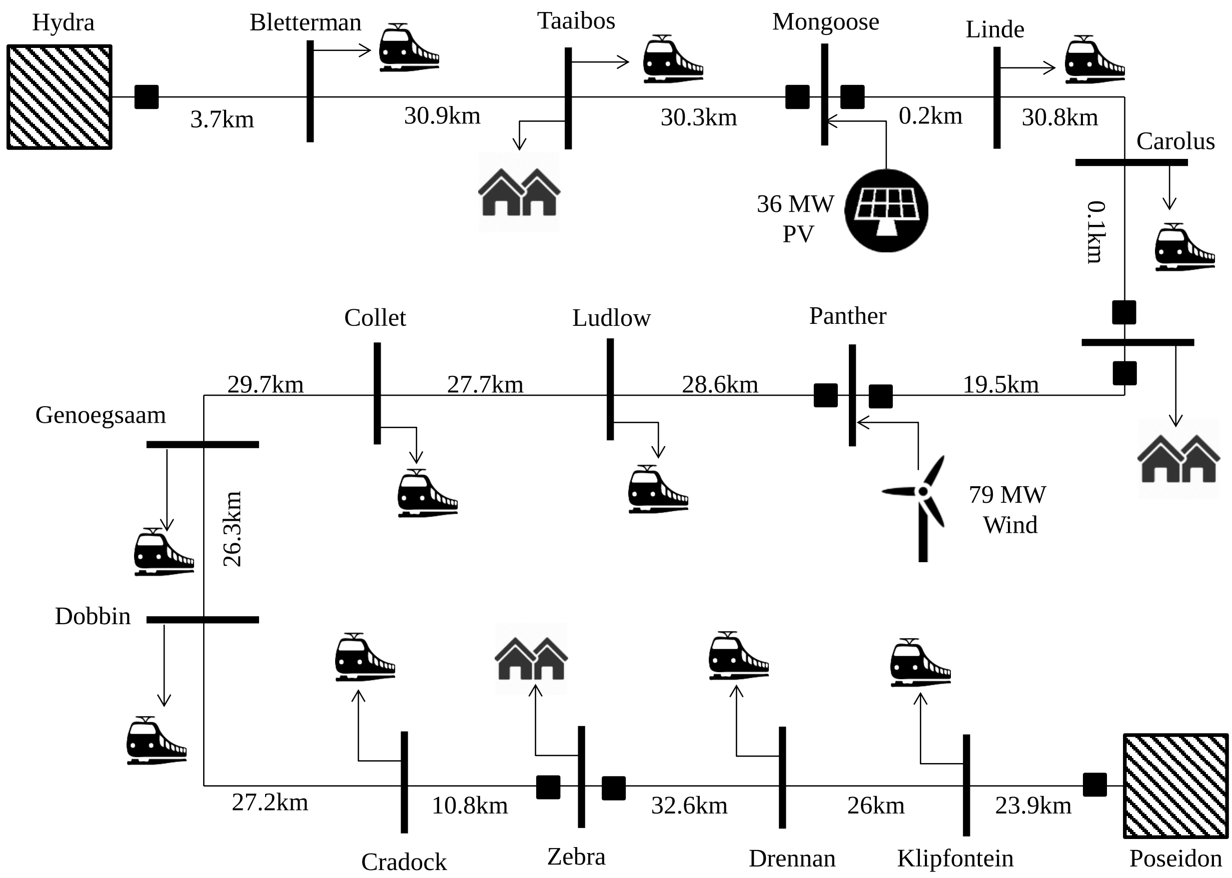

Figure 4-1: Schematic view: Hydra – Poseidon 132 kV sub-transmission network

Total length of the 132 kV network is 348.59 km. BEAR conductor was used to construct the line which has a current capacity of 512 A under normal conditions (rate A) and 767 A under contingency operating conditions (rate B). Hydra and Poseidon are also connected via 2 x 400 kV lines.

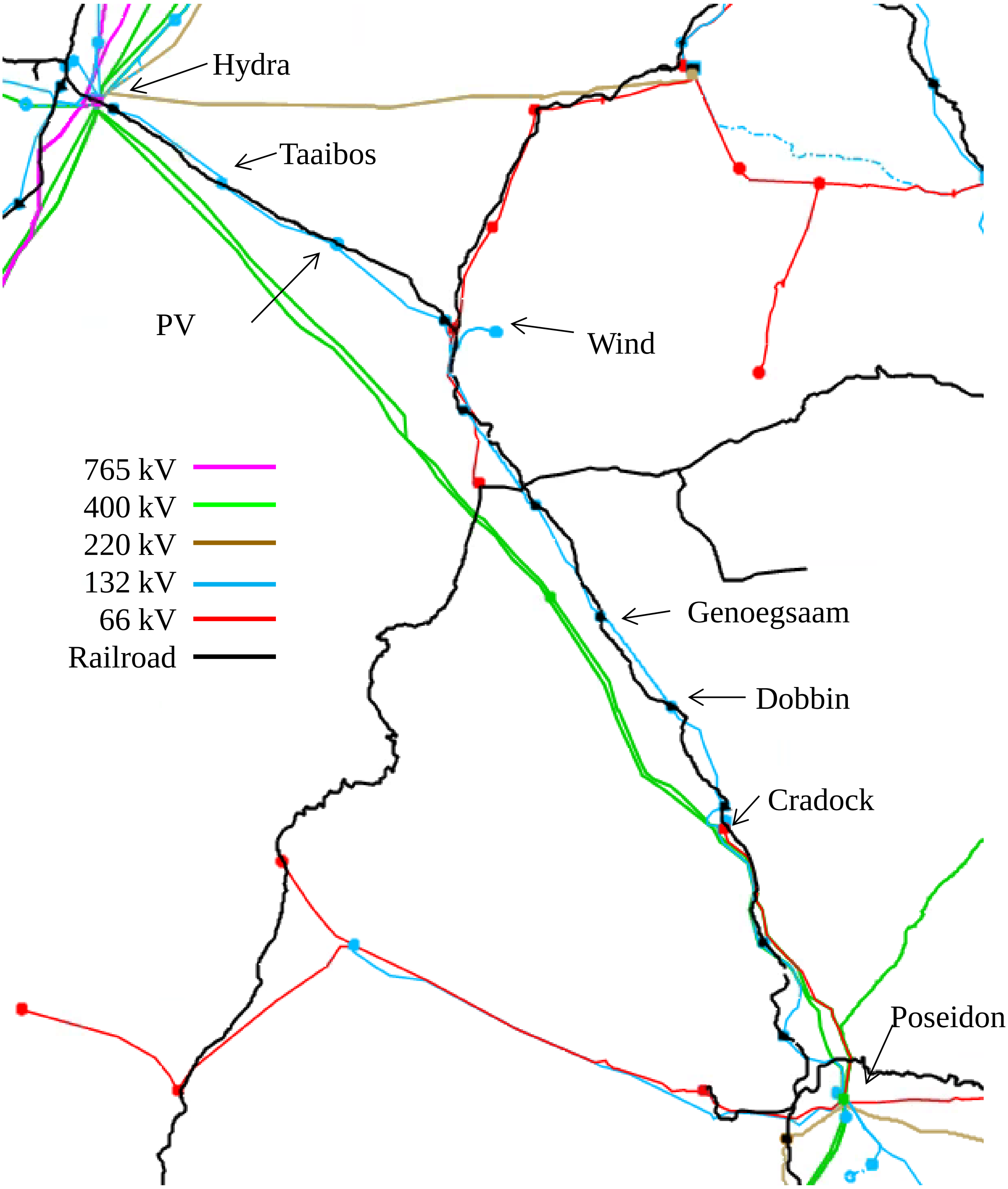

Figure 4-2: Geographic view: Hydra – Poseidon 132 kV sub-transmission network

4.1.2 Network loading

Figure 4-3 shows the network loading (red) and generation (blue). Generation exceeds load 73.65% of the time, the network is a nett exporter of active power.

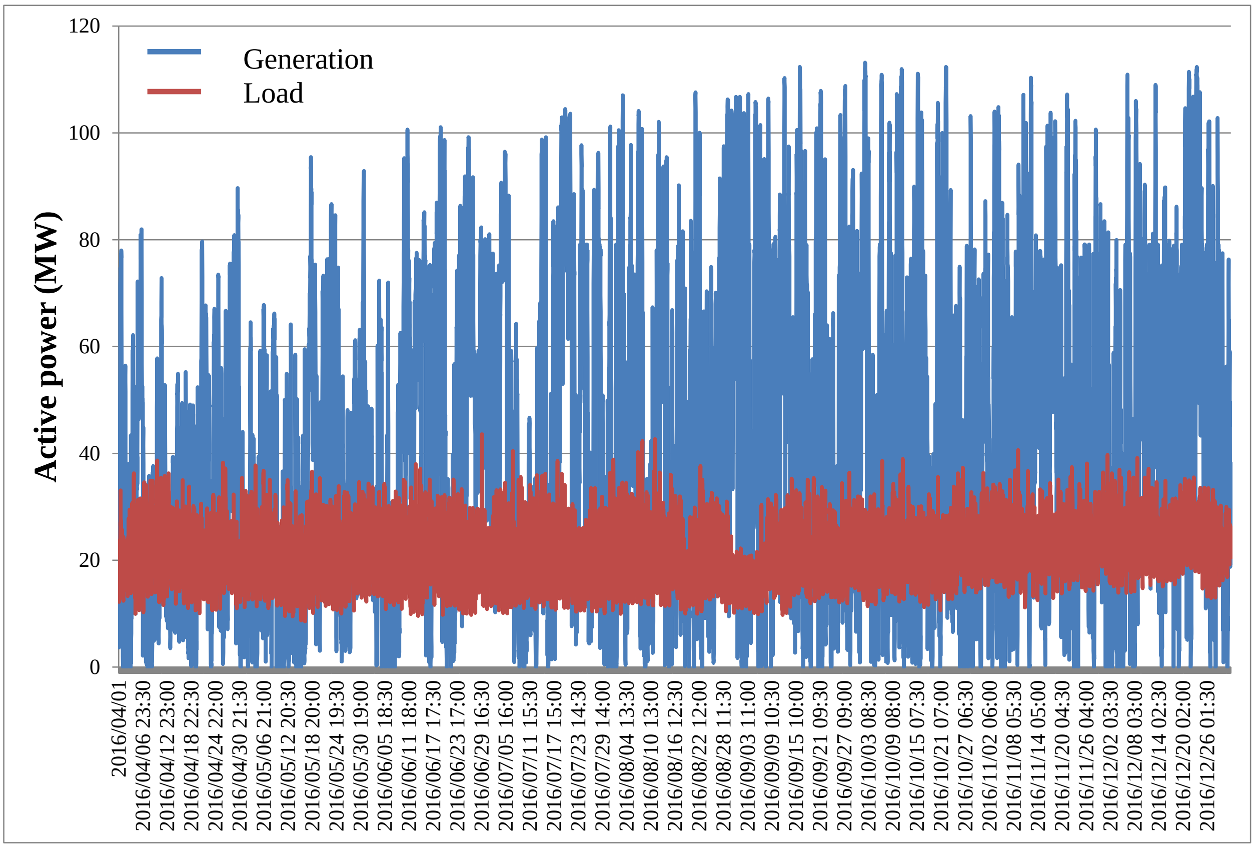

Figure 4-3: Load (red) and generation (blue)

Figure 4-4: Typical network loading/ generation during high generation period

Figure 4-4 represents a high generation scenario (with both wind and PV generating at full power) with loading for a 24 h period. Data plotted is 30 min averaged values. Network loading consists of residential load and traction load. Residential load has the expected morning and evening peaks. Traction load is much more intermitted.

4.1.3 Connected renewables

Construction of the wind energy facility (WEF) started construction in May 2015 under the third bid window of the IPP program and reached commercial operation on 11 July 2016 [52]. Installed capacity is 80.1 MW. MEC is capped at 79 MW, consisting of 35 Siemens SWT-2.3-108 (2.3 MW) wind turbines. Reactive power capability according to the grid code is based on the MEC at the PoC is ±26.07 MVAr.

The WEF is connected to Eskom's 132 kV sub-transmission network via a loop in loop out arrangement at the newly constructed Panther switching station. A 132/33 kV 90 MVA Ynd1 transformer with a NEC is used as a main grid transformer.

MEC of the PV facility is 36 MW. It uses a single axis tracking system with SMA inverters [53]. It is connected to the 132 kV grid via a newly constructed switching station, Mongoose. Main grid transformers are 2 x 132/33 kV 20 MVA Ynd1 transformers with a NEC.

Preferred bidder status was awarded in April 2013 under the second bid round of the IPP programme. Commercial operation was reached in Oct 2014. Reactive power capability of the plant, according to the grid code is ±11.88 MVAr.

Table 4-1: Summary of connected renewables

	WEF	PV
Technology	On shore wind	Single axis tracking PV
MEC (MW)	79	36
Reactive power capability (MVAr)	±26.07	±11.88

4.1.4 Network conditions

During normal grid conditions, the RE generators are connected to Hydra and Poseidon. The critical network contingency (which will result in the largest reduction in fault level) occurs when the connection to Hydra is lost. Both facilities are then radially connected to Poseidon.

4.1.5 Simulation setup

The network shown in Figure 4-1 was modelled using PowerFactory®. IEC60909 method was used to calculate the fault level under various network contingencies. Fault level contribution from converter controller renewable generation is at most 1.5 times rated current as seen in sections 2.1.1 and 2.1.2.

Table 4-2 lists the fault levels on the network under different configurations. It is clear that there is a significate reduction in fault level during weak grid conditions.

Table 4-2: Calculated Fault levels

		Fault level (MVA) Normal grid conditions	Fault level (MVA) Weak grid conditions	Reduction in fault level (%)
Panther (WEF)	Generation	582.2	235.2	59.60%
	No-generation	508.9	161.6	68.25%
Mongoose (PV)	Generation	735.0	190.5	74.08%
	No-generation	683.6	139.4	79.61%

Using the values from Table 4-2 and Equation (7) the SCR for normal and weak network conditions at the PoC of the renewable generators are captured in Table 4-3.

Table 4-3: Short circuit ratio

		Normal grid conditions	Weak grid conditions
Panther (WEF)	Fault level (MVA)	582.2	235.2
	Rated plant output (MVA)	79.05	79.05
	SCR	7.365	2.975
Mongoose (PV)	Fault level (MVA)	735	190.5
	Rated plant output (MVA)	37	37
	SCR	19.865	5.149

The weakest grid condition is materialized when the strongest source is disconnected from the grid. To simulate the weakest grid conditions, the 132 kV Hydra – Bletterman breaker was opened. According to [28], a network is considered "weak" if the SCR is less than 10.

Under normal grid conditions, the network at Panther (WEF) is already considered "weak", but under *n-1* the network becomes extremely weak due to the reduction in fault level. When the reduction in fault level is so significate, voltage regulation and voltage unbalance becomes an issue.

4.1.6 Simulation results

Simulation results are dividend in balanced and unbalanced simulations. Balanced simulation studies are used to determine the most effective reactive power control mode and set point under various load/generation scenarios and network contingencies. Power voltage analysis is performed to determine the voltage rise attributed only to active power injection under normal and weak grid conditions.

Unbalanced simulation studies will show the effect traction networks have on voltage unbalance. Traction loads are modelled as unbalanced loads using load data from the metering database. Simulation were conducted in accordance to Eskom's guideline for Quality of supply simulations [54] in order to determine the effect the unbalanced traction loads has on voltage unbalance.

4.1.6.1 Balanced simulation results

Table 4-4 summaries the various simulations done in order to determine the optimal reactive power control mode under different network loading conditions and contingencies. Its shows the 132 kV busbar voltages of the various substations in the 132 kV ring. Substations are arranged in the physical order they appear in the network as shown in Figure 4-1.

Simulation 1 – High generation high load under normal network conditions and both generating plant's reactive power control mode set to unity power factor mode (zero reactive power exchanged at the PoC between the RE generator and the grid). Voltages at the beginning (Hydra) and end (Poseidon) are kept constant by the 400/132 kV tap changers. There is a voltage rise at the point of generation as expected, most notability at Panther switching station where the WEF injects 79 MW.

Table 4-4: Summary of simulation results

	1		2		3		4		5	
	HGHL - Normal - PF		HGLL - Normal - PF		HGHL - Weak - PF		HGLL - Weak - PF		HGLL - Weak - Voltage	
Substation Busbar	kV	pu	kV	pu	kV	pu	kV	pu	kV	pu
Hydra 132 BB2	134.28	1.017	134.25	1.017	133.93	1.015	133.95	1.015	133.92	1.015
Bletterman Traction 132 BB	134.47	1.019	134.50	1.019	139.71	1.058	144.28	1.093	137.11	1.039
Taaibos 132 BB 1	136.13	1.031	136.70	1.036	139.72	1.059	144.18	1.092	137.01	1.038
Mongoose 132 BB 1	137.86	1.044	138.87	1.052	139.85	1.059	144.00	1.091	136.83	1.037
Linde Traction 132 BB	137.87	1.044	138.89	1.052	139.84	1.059	143.98	1.091	136.82	1.037
Carolus Traction 132 BB	138.62	1.050	140.06	1.061	138.92	1.052	142.75	1.081	135.97	1.030
Newgate 132 BB 1	138.62	1.050	140.07	1.061	138.92	1.052	142.75	1.081	135.97	1.030
Panther 132 BB 1	138.96	1.053	140.45	1.064	138.79	1.051	142.45	1.079	135.80	1.029
Ludlow Traction 132 BB 1	138.15	1.047	139.76	1.059	136.69	1.036	140.00	1.061	133.66	1.013
Collett Traction 132 BB 1	137.38	1.041	139.03	1.053	134.86	1.022	137.80	1.044	131.87	0.999
Genoegsaam Traction 132 BB 1	136.74	1.036	138.34	1.048	133.34	1.010	135.95	1.030	130.58	0.989
Dobbin Traction 132 BB 1	136.31	1.033	137.80	1.044	132.37	1.003	134.76	1.021	130.00	0.985
Cradock Traction 132 BB 1	136.02	1.030	137.35	1.041	131.74	0.998	134.01	1.015	129.98	0.985
Zebra 132 BB 1	135.96	1.030	137.19	1.039	131.60	0.997	133.84	1.014	130.12	0.986
Drennan Traction 132 BB 1	136.53	1.034	137.24	1.040	132.04	1.000	134.20	1.017	131.52	0.996
Klipfontein Traction 132 BB 1	136.98	1.038	137.31	1.040	132.60	1.005	134.86	1.022	133.06	1.008
Poseidon 132 BB1	137.39	1.041	137.38	1.041	133.26	1.010	135.74	1.028	134.80	1.021

Simulation 2 – High generation low load under normal network conditions and both generating plant's reactive power control mode set to unity power factor mode. With this scenario, the voltage rise associated with the power generation is heightened (comparing to simulation 1) due a reduction in network loading.

Simulations 1 and 2 indicate that some reactive power compensation control is required to limit the upper voltage limit to below 1.05 pu under normal network conditions.

Weak grid conditions are simulated in simulations 3 to 5.

Simulation 3 – High generation high load under weak network conditions (*n-1*) and both generating plant's reactive power control mode set to unity power factor mode. The Hydra 132 kV busbar is not connected to the rest of the 132 kV ring. Voltage increases along the radially connected line as expected and peaks at the end of the line.

Simulation 4 – High generation low load under weak network conditions (*n-1*) and both generating plant's reactive power control mode set to unity power factor mode. The voltage at the end of the sub-transmission line is higher compared to simulation 3 due to the lower network loading.

Simulation 5 – High generation low load under weak network conditions (*n-1*) and both generating plant's reactive power control mode set to voltage control mode. In this scenario, the distributed generators regulate the voltage along the line. Co-ordinated voltage control mitigates the voltage rise associated with low load and weak grid conditions.

4.1.6.2 Power voltage curve

The power voltage curve shows the generated active power contribution to voltage rise under normal and weak grid conditions. In Figure 4-5 the 132 kV PoC voltage is plotted for Mongoose (PV) and Panther (Wind) under normal and weak grid conditions. Reactive power was kept at zero and active power was increased from 0 % to 100 % in increments of 10 %.

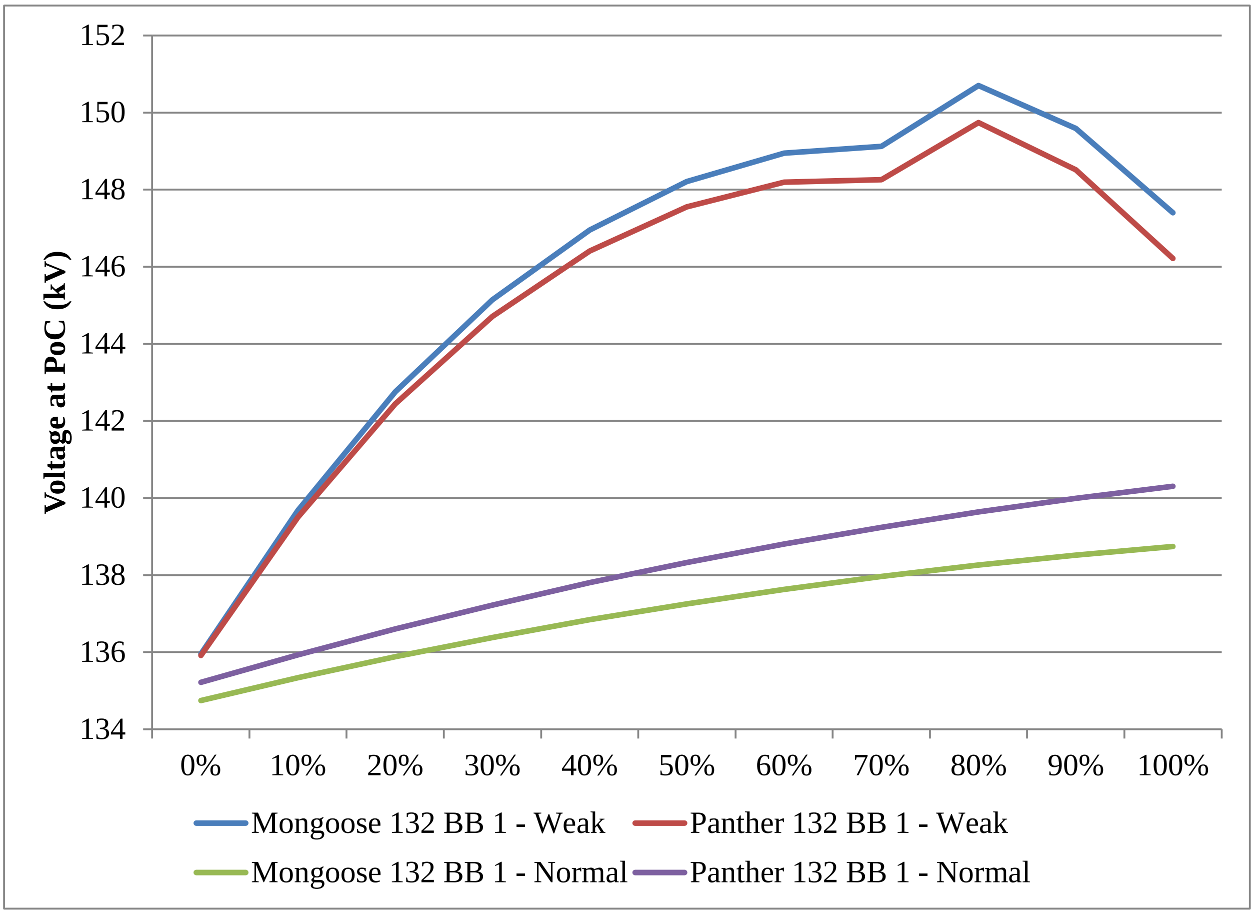

Figure 4-5: Power voltage curve during normal and weak grid conditions

During normal grid conditions with zero reactive power contribution, the voltage rise attributed to full active power generation is 4 kV (for the PV) and 5 kV (for the wind). Under weak grid conditions, the voltage rise attributed to full active power generation is 14.7 kV (for the PV) and 13.8 kV (for the wind). This shows a substantial increase in voltage, especially under weak grid conditions.

Normally the increase in voltage due to active power generation is a linear relationship. However, under weak grid conditions during high power transfer, the reactive power consumption of the line can increase substantially resulting in a lower voltage at the PoC [55]. This is an indication of an unstable network that could lead to voltage collapse.

4.1.6.3 Unbalanced simulation results

Traction loads were modelled as single phase traction loads distributed at the various substations along the railway. Table 4-5 shows the voltage unbalance at various busbars in the sub-transmission network during normal and weak grid conditions with the RE generation disconnected. Loading between the two scenarios remained unchanged. Voltage unbalance increases as the network fault level decreases with the critical contingency.

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Table 4-5: Unbalanced load flow analysis with no generation

	Normal grid - generation disconnected						Weak grid - generation disconnected					
Substation name	Phase A (pu)	Phase B (pu)	Phase C (pu)	Positive sequence voltage (kV)	Negative sequence voltage (kV)	Voltage unbalance (%)	Phase A (pu)	Phase B (pu)	Phase C (pu)	Positive sequence voltage (kV)	Negative sequence voltage (kV)	Voltage unbalance (%)
Hydra 132 BB2	1.01627	1.01559	1.02218	134.3772	0.552874	0.41%	1.01304	1.01365	1.01677	133.9119	0.304737	0.23%
Bletterman Traction 132 BB	1.01581	1.01546	1.023	134.3872	0.649532	0.48%	1.00606	1.03127	1.13958	139.5593	11.01044	7.89%
Taaibos 132 BB 1	1.01208	1.01406	1.03007	134.469	1.50776	1.12%	1.00535	1.03056	1.13877	139.4609	11.00163	7.89%
Mongoose 132 BB 1	1.00898	1.01251	1.03721	134.5726	2.353842	1.75%	1.00379	1.02894	1.13697	139.2427	10.98215	7.89%
Linde Traction 132 BB	1.00894	1.01249	1.03731	134.5738	2.365537	1.76%	1.00376	1.02891	1.13693	139.2386	10.98179	7.89%
Carolus Traction 132 BB	1.00602	1.01045	1.04451	134.6638	3.22872	2.40%	1.00102	1.02611	1.13379	138.857	10.94768	7.88%
Newgate 132 BB 1	1.00603	1.01046	1.04451	134.6646	3.228239	2.40%	1.00103	1.02612	1.13378	138.8572	10.94604	7.88%
Panther 132 BB 1	1.00887	1.01333	1.04596	134.9813	3.103719	2.30%	1.00255	1.0279	1.13088	138.892	10.53854	7.59%
Ludlow Traction 132 BB 1	1.01476	1.01941	1.04811	135.6064	2.766037	2.04%	1.0068	1.03176	1.12207	138.9048	9.379776	6.75%
Collett Traction 132 BB 1	1.01917	1.02434	1.04919	136.0675	2.456676	1.81%	1.01076	1.03472	1.11301	138.848	8.251391	5.94%
Genoegsaam Traction 132 BB 1	1.02386	1.0286	1.0503	136.513	2.155767	1.58%	1.01517	1.03648	1.10305	138.7152	7.059149	5.09%
Dobbin Traction 132 BB 1	1.02733	1.03183	1.0506	136.8227	1.88772	1.38%	1.01852	1.03716	1.09345	138.4954	5.99638	4.33%
Cradock Traction 132 BB 1	1.0315	1.03415	1.05006	137.0869	1.53412	1.12%	1.02106	1.03806	1.08354	138.2319	4.956119	3.59%
Zebra 132 BB 1	1.03242	1.03506	1.04973	137.1534	1.424402	1.04%	1.02204	1.03778	1.07927	138.0819	4.532939	3.28%
Drennan Traction 132 BB 1	1.037	1.03918	1.05014	137.5559	1.074777	0.78%	1.02712	1.03789	1.06713	137.796	3.168853	2.30%
Klipfontein Traction 132 BB 1	1.03971	1.04166	1.04962	137.7625	0.800997	0.58%	1.03066	1.03712	1.05706	137.4848	2.104029	1.53%
Poseidon 132 BB1	1.04212	1.04292	1.04881	137.8888	0.557134	0.40%	1.03416	1.03534	1.04773	137.1557	1.148735	0.84%

An increase in voltage unbalance was expected as defined by equation (15) when the fault level reduced.

$$UB = \frac{P_{load}}{S_{SSC}}$$

Load remained the unchanged, but the fault level decreased as shown in Table 4-2.

Not only is the voltage unbalance extremely high, on one phase the voltage is above 1.1 pu. If the voltage persists above 1.1 pu for longer than 2 seconds, it is outside the criteria for a successful HVRT event – thus the renewables could disconnect.

The simulations above are repeated with the generation connected and exporting at full power and operating in voltage control mode (as recommended by the previous results) with the results shown in Table 4-6.

Table 4-6: Unbalanced load flow analysis with renewable operating in voltage control mode

	Normal grid - Wind & PV in Voltage control mode						Weak grid - PV & Wind in Voltage control mode					
Substation Name	Phase A (pu)	Phase B (pu)	Phase C (pu)	Positive sequence voltage (kV)	Negative sequence voltage (kV)	Voltage unbalance (%)	Phase A (pu)	Phase B (pu)	Phase C (pu)	Positive sequence voltage (kV)	Negative sequence voltage (kV)	Voltage unbalance (%)
Hydra 132 BB2	1.01309	1.01173	1.01871	133.9145	0.564181	0.42%	1.01339	1.01335	1.01692	133.9209	0.312791	0.23%
Bletterman Traction 132 BB	1.01407	1.01208	1.02046	134.0502	0.667915	0.50%	1.01999	0.9767	1.12063	136.9169	11.42212	8.34%
Taaibos 132 BB 1	1.02215	1.01501	1.0354	135.1879	1.579664	1.17%	1.01927	0.97602	1.11983	136.8204	11.4125	8.34%
Mongoose 132 BB 1	1.02963	1.01799	1.05002	136.2851	2.476419	1.82%	1.01769	0.97449	1.11806	136.6064	11.39285	8.34%
Linde Traction 132 BB	1.02964	1.01798	1.05015	136.2908	2.487839	1.83%	1.0176	0.9744	1.11796	136.5941	11.39184	8.34%
Carolus Traction 132 BB	1.0301	1.01646	1.05913	136.63	3.333771	2.44%	1.01109	0.96733	1.1101	135.6528	11.31086	8.34%
Newgate 132 BB 1	1.03011	1.01647	1.05913	136.631	3.33333	2.44%	1.01109	0.96733	1.11009	135.6523	11.30925	8.34%
Panther 132 BB 1	1.0335	1.01784	1.0599	136.8749	3.249092	2.37%	1.01288	0.96777	1.10659	135.6129	10.93373	8.06%
Ludlow Traction 132 BB 1	1.03174	1.0194	1.05557	136.6805	2.810145	2.06%	1.00516	0.96058	1.08423	134.0225	9.636675	7.19%
Collett Traction 132 BB 1	1.02969	1.01992	1.05091	136.4119	2.421618	1.78%	0.99862	0.95552	1.06427	132.6753	8.40225	6.33%
Genoegsaam Traction 132 BB 1	1.02864	1.02079	1.0473	136.2484	2.080827	1.53%	0.99495	0.95443	1.0476	131.7692	7.148066	5.42%
Dobbin Traction 132 BB 1	1.02802	1.02217	1.04467	136.1679	1.784178	1.31%	0.99394	0.9575	1.03644	131.3967	6.034411	4.59%
Cradock Traction 132 BB 1	1.03034	1.02268	1.04212	136.1819	1.494319	1.10%	0.9998	0.96232	1.02809	131.5217	5.019583	3.82%
Zebra 132 BB 1	1.0303	1.02361	1.04139	136.1898	1.370791	1.01%	1.00083	0.9661	1.02598	131.6486	4.574082	3.47%
Drennan Traction 132 BB 1	1.03264	1.02877	1.0416	136.5309	1.004441	0.74%	1.00828	0.98337	1.02477	132.7034	3.170798	2.39%
Klipfontein Traction 132 BB 1	1.0345	1.03306	1.04204	136.8215	0.735617	0.54%	1.01586	1.00007	1.0273	133.8941	2.081871	1.55%
Poseidon 132 BB1	1.03677	1.03674	1.04291	137.122	0.541954	0.40%	1.02466	1.0172	1.03248	135.2684	1.164242	0.86%

During normal conditions, the plants are successful in regulating the voltage. Voltage unbalance during normal conditions with the renewable generation operating in voltage control mode remains relatively unchanged compared to normal grid conditions without generation. This is because the renewable generation does not add significant fault level to the grid as seen in Table 4-2.

Table 4-6 also shows the voltage for the network under weak grid conditions whilst operating in voltage control mode. There is small increase in voltage unbalance and voltages are lower (than compared to the weak grid simulation in Table 4-5) because the RE generators are absorbing reactive power. However the voltage on one phase still exceeds 1.1 pu, which will cause the RE generator to disconnect.

Operating the RE generators in voltage control mode does not reduce the voltage unbalance nor is it able to effectively regulate the voltage on all three phases (as shown in the balanced simulation studies). It does not make sense to operate the RE facilities in voltage control mode under weak grid conditions.

Table 4-7 compares voltage control mode and constant Q control mode under weak grid conditions since voltage control did not provide adequate control.

Table 4-7: Comparison of voltage and Q mode under weak grid conditions

	Weak grid - PV and Wind in V mode						Weak grid - PV and Wind in Q mode					
Substation Name	Phase A (pu)	Phase B (pu)	Phase C (pu)	Positive sequence voltage (kV)	Negative sequence voltage (kV)	Voltage unbalance (%)	Phase A (pu)	Phase B (pu)	Phase C (pu)	Positive sequence voltage (kV)	Negative sequence voltage (kV)	Voltage unbalance (%)
Hydra 132 BB2	1.01339	1.01335	1.01692	133.9209	0.312791	0.23%	1.01329	1.0132	1.01675	133.9025	0.308982	0.23%
Bletterman Traction 132 BB	1.01999	0.9767	1.12063	136.9169	11.42212	8.34%	0.97776	0.9304	1.06965	130.7896	10.9284	8.36%
Taaibos 132 BB 1	1.01927	0.97602	1.11983	136.8204	11.4125	8.34%	0.97706	0.92976	1.06888	130.6974	10.91916	8.35%
Mongoose 132 BB 1	1.01769	0.97449	1.11806	136.6064	11.39285	8.34%	0.97556	0.92831	1.06721	130.4945	10.90067	8.35%
Linde Traction 132 BB	1.0176	0.9744	1.11796	136.5941	11.39184	8.34%	0.97547	0.92821	1.0671	130.481	10.89945	8.35%
Carolus Traction 132 BB	1.01109	0.96733	1.1101	135.6528	11.31086	8.34%	0.96842	0.92065	1.05854	129.4643	10.80384	8.35%
Newgate 132 BB 1	1.01109	0.96733	1.11009	135.6523	11.30925	8.34%	0.96842	0.92065	1.05852	129.4637	10.80231	8.34%
Panther 132 BB 1	1.01288	0.96777	1.10659	135.6129	10.93373	8.06%	0.97001	0.9208	1.05486	129.3946	10.44656	8.07%
Ludlow Traction 132 BB 1	1.00516	0.96058	1.08423	134.0225	9.636675	7.19%	0.96444	0.91591	1.03507	128.1112	9.197638	7.18%
Collett Traction 132 BB 1	0.99862	0.95552	1.06427	132.6753	8.40225	6.33%	0.96059	0.91383	1.01833	127.1541	8.010597	6.30%
Genoegsaam Traction 132 BB 1	0.99495	0.95443	1.0476	131.7692	7.148066	5.42%	0.9606	0.9169	1.00612	126.7875	6.8085	5.37%
Dobbin Traction 132 BB 1	0.99394	0.9575	1.03644	131.3967	6.034411	4.59%	0.9635	0.92442	0.99976	126.9929	5.742147	4.52%
Cradock Traction 132 BB 1	0.9998	0.96232	1.02809	131.5217	5.019583	3.82%	0.97429	0.93456	0.99678	127.8029	4.783341	3.74%
Zebra 132 BB 1	1.00083	0.9661	1.02598	131.6486	4.574082	3.47%	0.97722	0.94049	0.99704	128.2122	4.356225	3.40%
Drennan Traction 132 BB 1	1.00828	0.98337	1.02477	132.7034	3.170798	2.39%	0.99125	0.96514	1.00406	130.2424	3.014401	2.31%
Klipfontein Traction 132 BB 1	1.01586	1.00007	1.0273	133.8941	2.081871	1.55%	1.0044	0.98797	1.0136	132.2553	1.976266	1.49%
Poseidon 132 BB1	1.02466	1.0172	1.03248	135.2684	1.164242	0.86%	1.01857	1.01091	1.02554	134.4189	1.115459	0.83%

None of the modes are capable of reducing the voltage unbalance, but Q mode reduces the phase voltages adequately to prevent the plant from tripping on over voltage, but causes low voltages on another phase.

Simulations in Table 4-7 are based on full active power output from both RE facilities. For the next simulation shown in Table 4-8, the network loading is kept the same as previous simulation but the generated power by the RE facilities are reduced to 10 % of rated output.

Table 4-8: Voltage reduction attributed to active power generation

Substation Name	Weak grid - Q mode; P = 100%						Weak grid - Q mode; P = 10%					
	Phase A (pu)	Phase B (pu)	Phase C (pu)	Positive sequence voltage (kV)	Negative sequence voltage (kV)	Voltage unbalance (%)	Phase A (pu)	Phase B (pu)	Phase C (pu)	Positive sequence voltage (kV)	Negative sequence voltage (kV)	Voltage unbalanc e (%)
Hydra 132 BB2	1.01329	1.0132	1.01675	133.9025	0.308982	0.23%	1.00282	1.0018	1.00524	132.434	0.26924	0.20%
Bletterman Traction 132 BB	0.97776	0.9304	1.06965	130.7896	10.9284	8.36%	0.86205	0.80979	0.93379	114.446	9.55995	8.35%
Taaibos 132 BB 1	0.97706	0.92976	1.06888	130.6974	10.91916	8.35%	0.86144	0.80923	0.93312	114.365	9.55182	8.35%
Mongoose 132 BB 1	0.97556	0.92831	1.06721	130.4945	10.90067	8.35%	0.86168	0.8091	0.93324	114.374	9.56743	8.37%
Linde Traction 132 BB	0.97547	0.92821	1.0671	130.481	10.89945	8.35%	0.86161	0.80902	0.93315	114.364	9.56633	8.36%
Carolus Traction 132 BB	0.96842	0.92065	1.05854	129.4643	10.80384	8.35%	0.85664	0.80317	0.92638	113.592	9.48002	8.35%
Newgate 132 BB 1	0.96842	0.92065	1.05852	129.4637	10.80231	8.34%	0.85664	0.80317	0.92637	113.592	9.47873	8.34%
Panther 132 BB 1	0.97001	0.9208	1.05486	129.3946	10.44656	8.07%	0.85881	0.80353	0.9235	113.59	9.19445	8.09%
Ludlow Traction 132 BB 1	0.96444	0.91591	1.03507	128.1112	9.197638	7.18%	0.85774	0.80336	0.909	112.941	8.05575	7.13%
Collett Traction 132 BB 1	0.96059	0.91383	1.01833	127.1541	8.010597	6.30%	0.86036	0.80826	0.89988	112.907	6.98619	6.19%
Genoegsaam Traction 132 BB 1	0.9606	0.9169	1.00612	126.7875	6.8085	5.37%	0.86969	0.8217	0.89886	113.895	5.91107	5.19%
Dobbin Traction 132 BB 1	0.9635	0.92442	0.99976	126.9929	5.742147	4.52%	0.88281	0.84053	0.9049	115.59	4.96096	4.29%
Cradock Traction 132 BB 1	0.97429	0.93456	0.99678	127.8029	4.783341	3.74%	0.90647	0.86434	0.91588	118.179	4.15299	3.51%
Zebra 132 BB 1	0.97722	0.94049	0.99704	128.2122	4.356225	3.40%	0.91443	0.87577	0.92231	119.321	3.77075	3.16%
Drennan Traction 132 BB 1	0.99125	0.96514	1.00406	130.2424	3.014401	2.31%	0.94641	0.9195	0.95122	123.94	2.59292	2.09%
Klipfontein Traction 132 BB 1	1.0044	0.98797	1.0136	132.2553	1.976266	1.49%	0.97447	0.95779	0.97888	128.085	1.69061	1.32%
Poseidon 132 BB1	1.01857	1.01091	1.02554	134.4189	1.115459	0.83%	1.00276	0.99512	1.00792	132.254	0.98119	0.74%

The amount of reactive power absorbed is also kept constant from the previous simulation (with active power at rated output). With the reduced generation output and the reactive power mode unchanged, the network experiences significantly lower voltages to the extent that the connected RE generators may disconnect for an LVRT event. The reduction in generation creates approximately 10 % difference. This correlates with the PV curve given in section 4.1.6.2.

This highlights the problem with operating RE generators in constant Q mode during weak grid conditions. Reactive power absorbed must be actively managed by the DSO. If the reaction of the DSO is not fast enough, the plant may trip on under or over voltage conditions. The amount of reactive power that needs to be absorbed is dependent on the active power output of both facilities and the load on the network.

Power factor control mode was not considered since it is not practical to implement. In power factor mode, reactive power cannot be controlled independently from active power. This might lead to a scenario that more reactive power is needed to counter act voltage rise, but the RE generators are unable to provide it due the current active power output.

4.1.6.4 Limitations of simulation studies

Loading data used in the simulation is averaged values over a 30 min period. Instantaneous load drawn could be much higher than the average value.

Traction loading is intermitted because it physically moves from one station to the next. It is also dependant on the elevation, direction of travel and the weight of the train. A train traveling on a downward slope consumes much less energy than a train on an upward slope. The simulation cannot account for all these different variables over a time period with limited data. Worst case loading conditions are therefore assumed to illustrate some of the effects on the network.

4.1.7 Summary

The critical network contingency was determined based on the SCR of the network. This contingency was used to determine the optimal reactive power control mode for the connected RE generators. However, accounting for the single phase AC traction loads, the voltage unbalance is simulated and shown to increase during the critical network contingency because of a reduction of fault level.

Constant Q mode was shown to be more effective than voltage control mode, but not without its own limitations. Active power injection of the RE generators have a substantial increase (up to 10 %) in voltage under weak grid conditions.

None of the reactive power control modes are capable of reducing the voltage unbalance. With close monitoring of the grid voltage, the DSO might have limited success to manually regulate the voltage.

4.2 Voltage ride through simulations

Simulations to proof compliance with the grid code requirements of LVRT and HVRT are shown. Models provided by the RE developers are merged with the network model. Simulations (done with PowerFactory®) will be based on a PV facility connected to a sub-transmission network.

4.2.1 Network layout and description

A 36 MW PV facility was commissioned in 2015. It is connected on the 132 kV sub-transmission line between Giraffe and KDS, shown in Figure 4-7 and Figure 4-6. The network is constructed with BEAR conductor with total length of 171.4 km. Ratings for BEAR conductor is shown in Table 4-9. A 36 MW

Table 4-9: BEAR conductor ratings

CONDUCTOR	RATE A	RATE B
BEAR	521 A (119 MVA @ 132 kV)	767 A (175 MVA @ 132 kV)

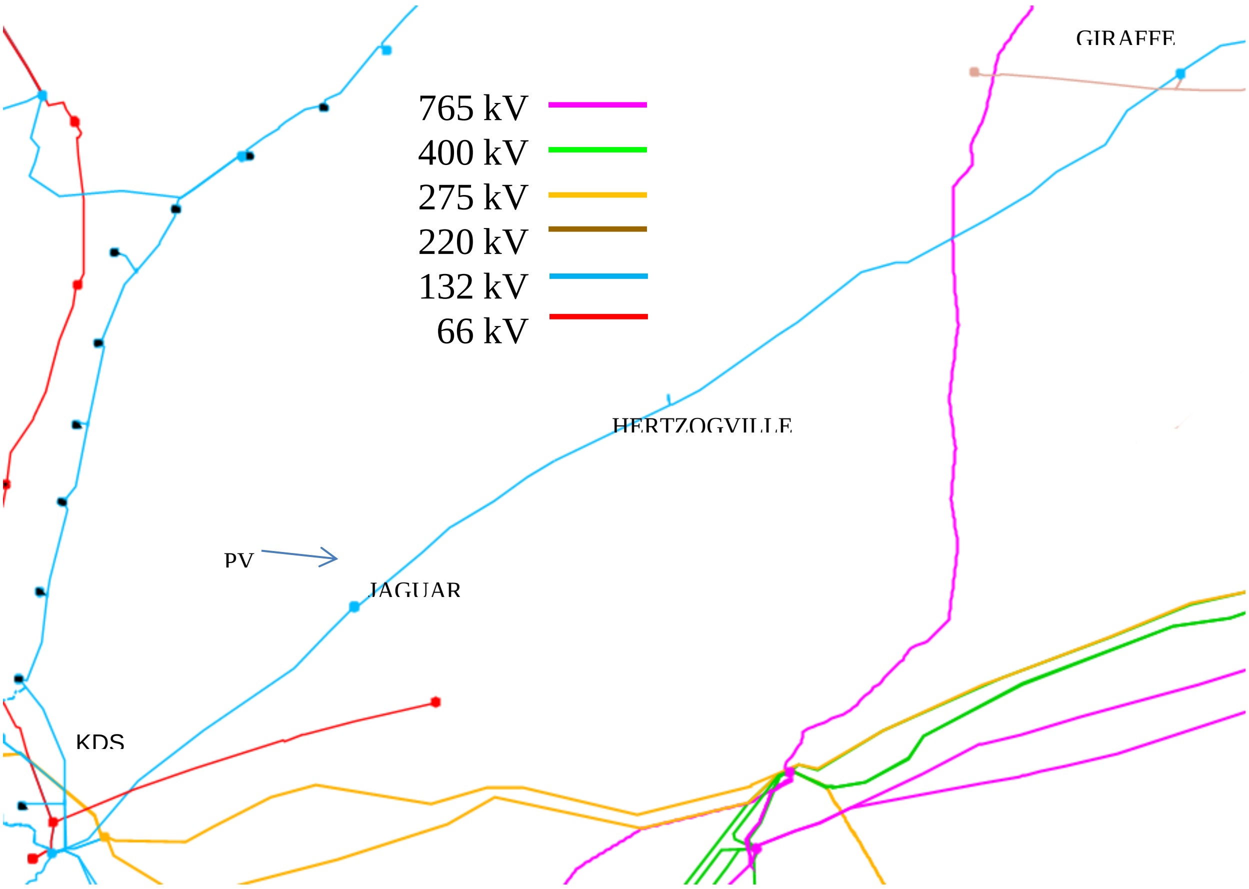

Figure 4-6: 132 kV geographic network layout

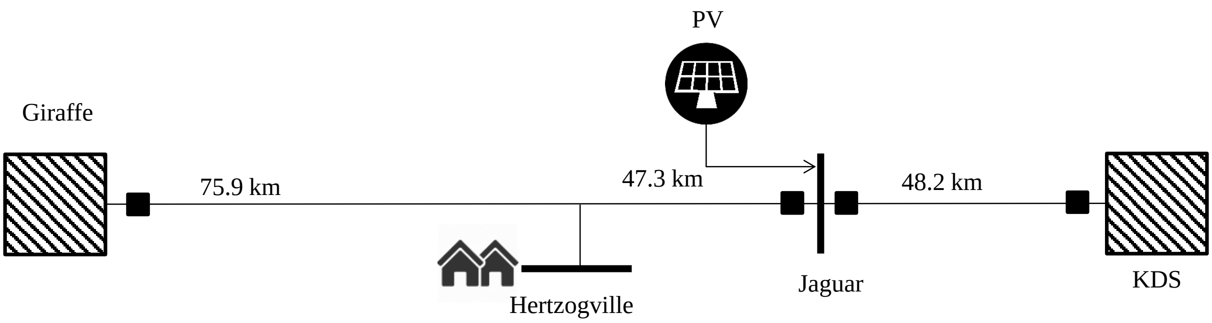

Figure 4-7: 132 kV network layout

4.2.2 Simulation setup

The PV generation model was supplied by the developer of the PV facility. These models were used to proof grid code compliance with regard to LVRT and HVRT.

For the low voltage ride through requirements, the worst possible fault that the facility should be able to successfully ride through was simulated: a balanced three phase fault resulting in the voltage dropping to 0 kV at the PoC for 150 ms.

The same principal was followed for the high voltage ride through: a voltage rise of 1.2 pu on all three phases at the PoC for 2 s.

4.2.3 Simulation results

Figure 4-8 shows the simulated 132 kV voltage profile at the PoC during a fault with Figure 4-9 showing the PV facility's response during the fault.

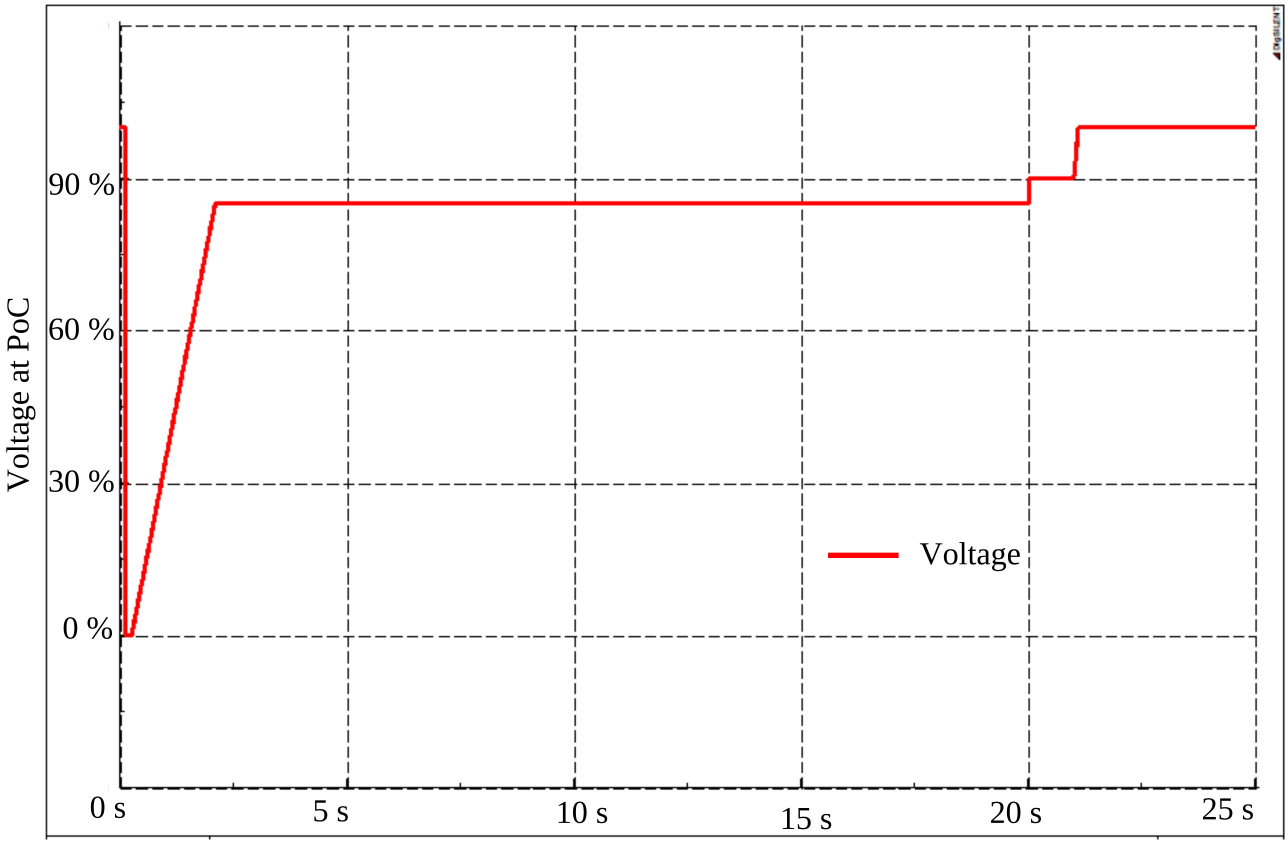

Figure 4-8: LVRT: 132 kV voltage at PoC

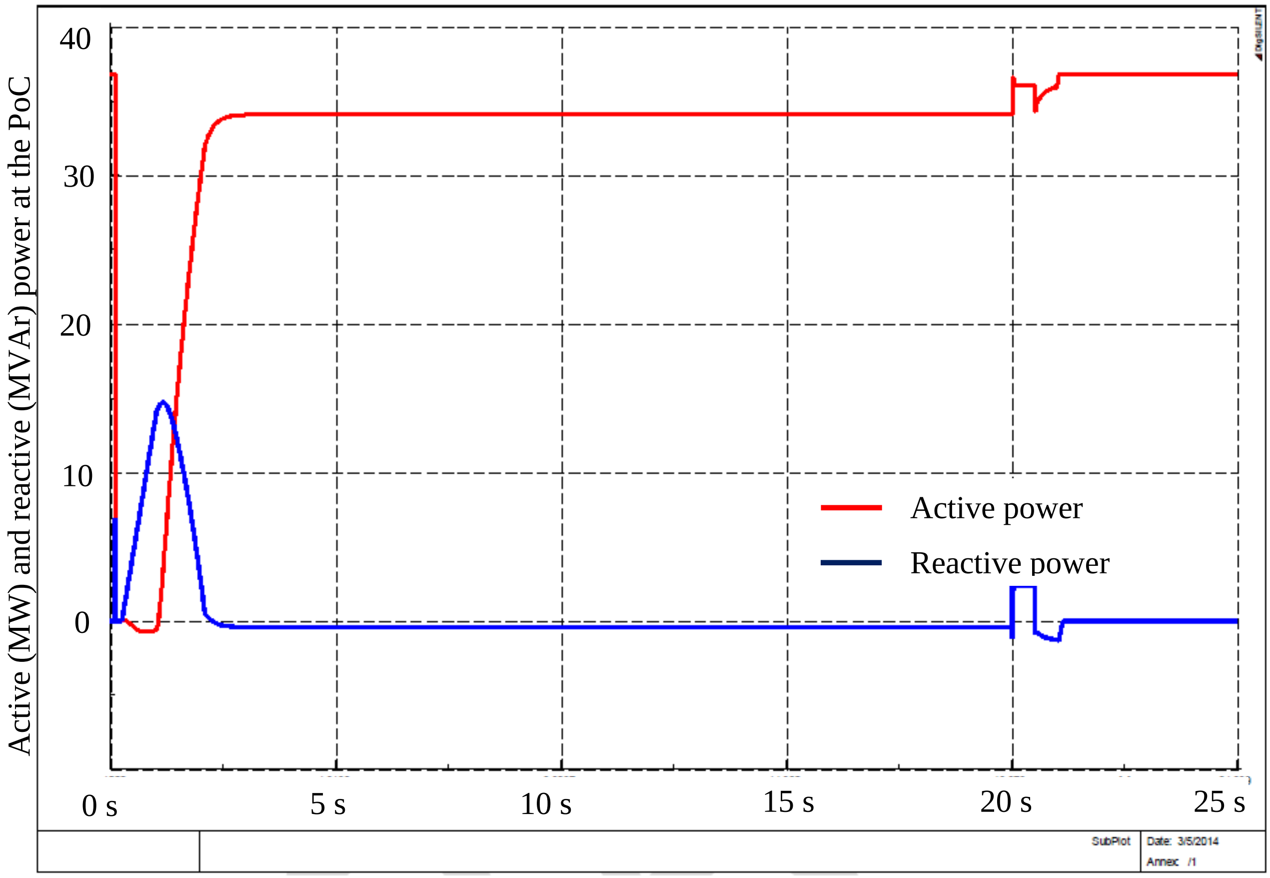

Figure 4-9: LVRT – Active (Red) and reactive (blue) power at PoC

In Figure 4-9 the active power in shown in red and reactive power in blue. As the fault occurs the active power reduces (as allowed by the grid code) and reactive power is pushed into the network in an attempt to stabilize the grid voltage. When the voltage recovers, the active and reactive power returns to pre-fault values. The PV facility does not disconnect as active power is resumed once the fault is cleared.

Figure 4-10 and Figure 4-11 shows the voltage, active and reactive power from the facility during two subsequent faults. Again the plant responded as required by the grid code.

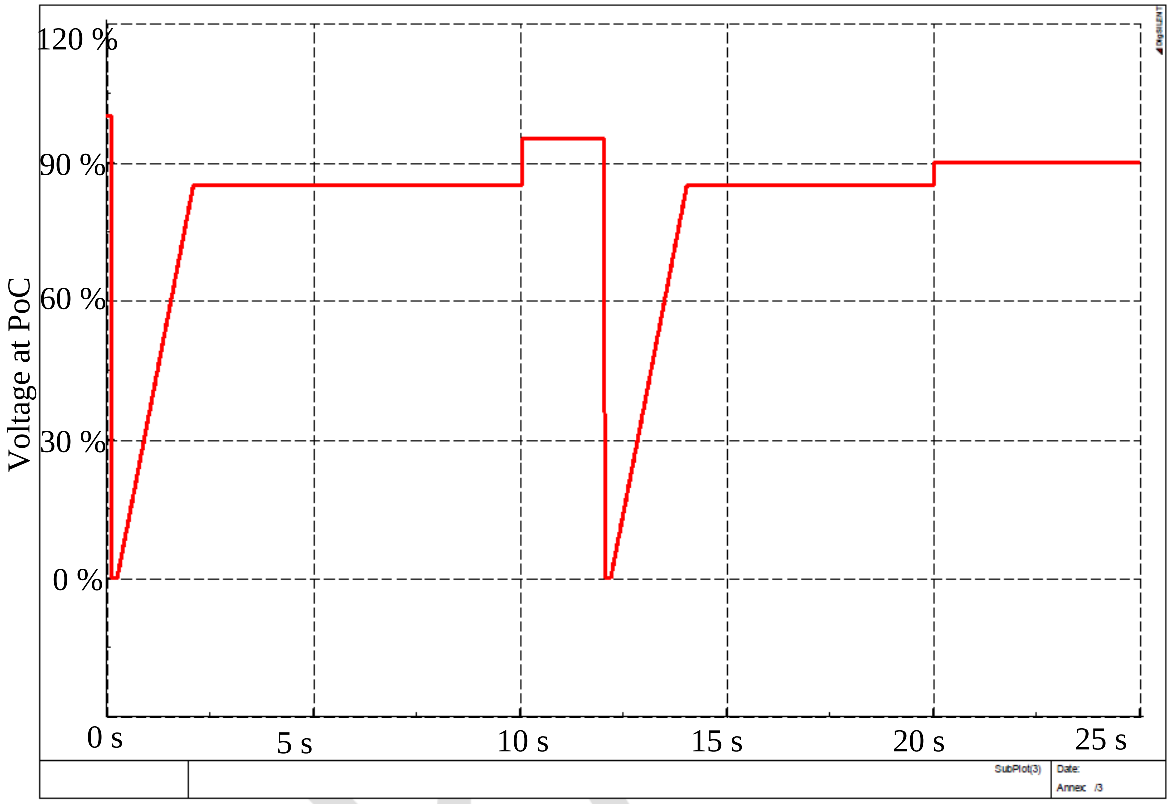

Figure 4-10: LVRT: 132 kV voltage at PoC for subsequent faults

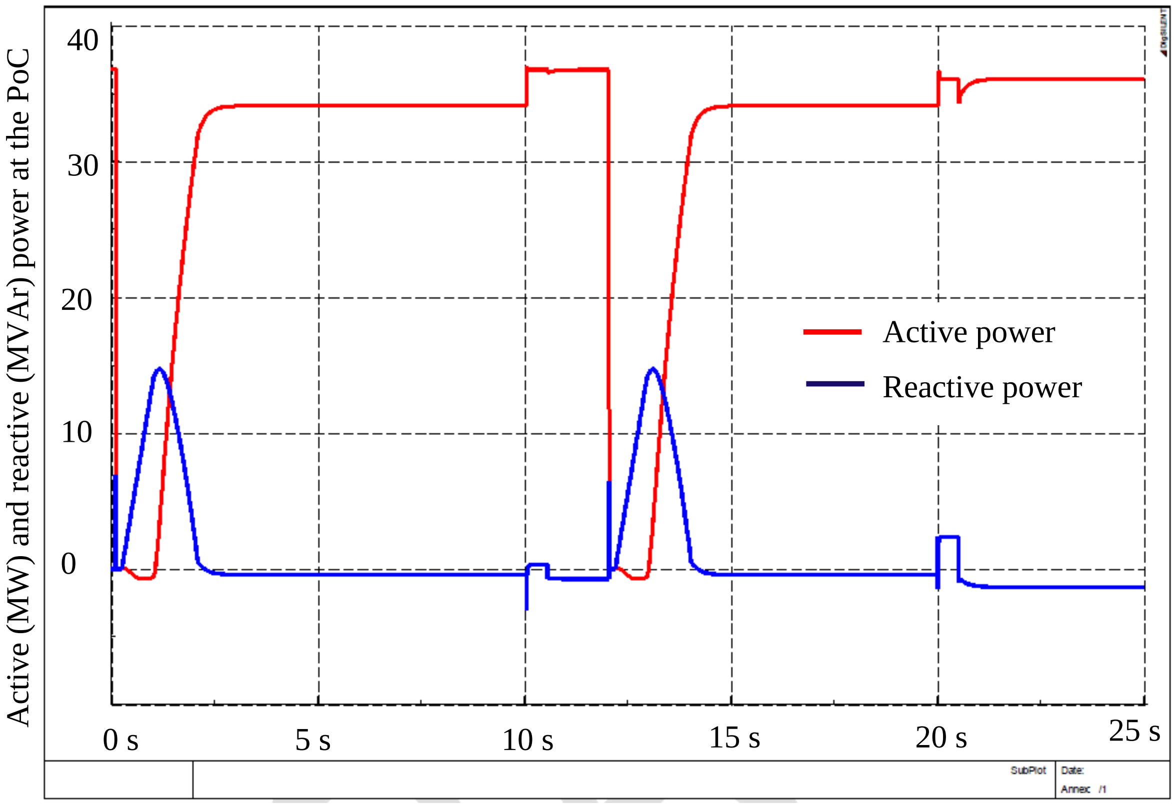

Figure 4-11: Active (red) and reactive (blue) power at PoC for subsequent faults

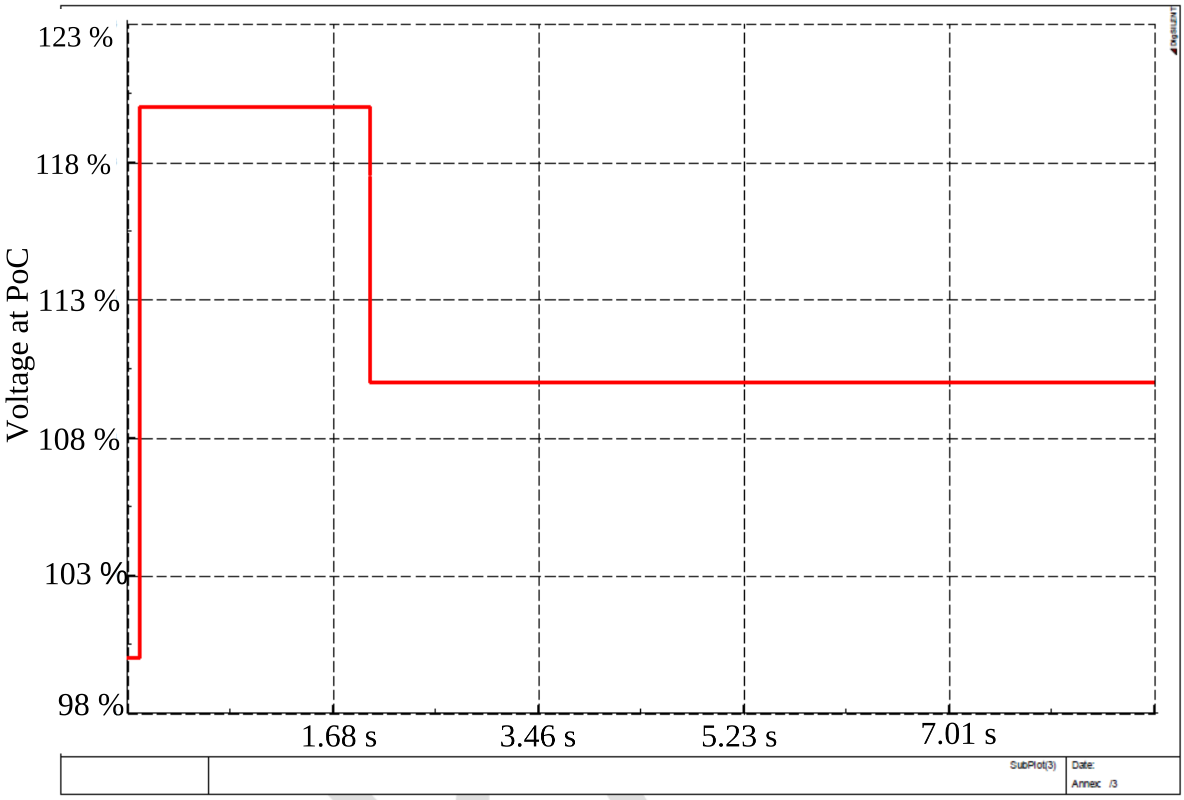

Figure 4-12: HVRT: 132 kV voltage at PoC

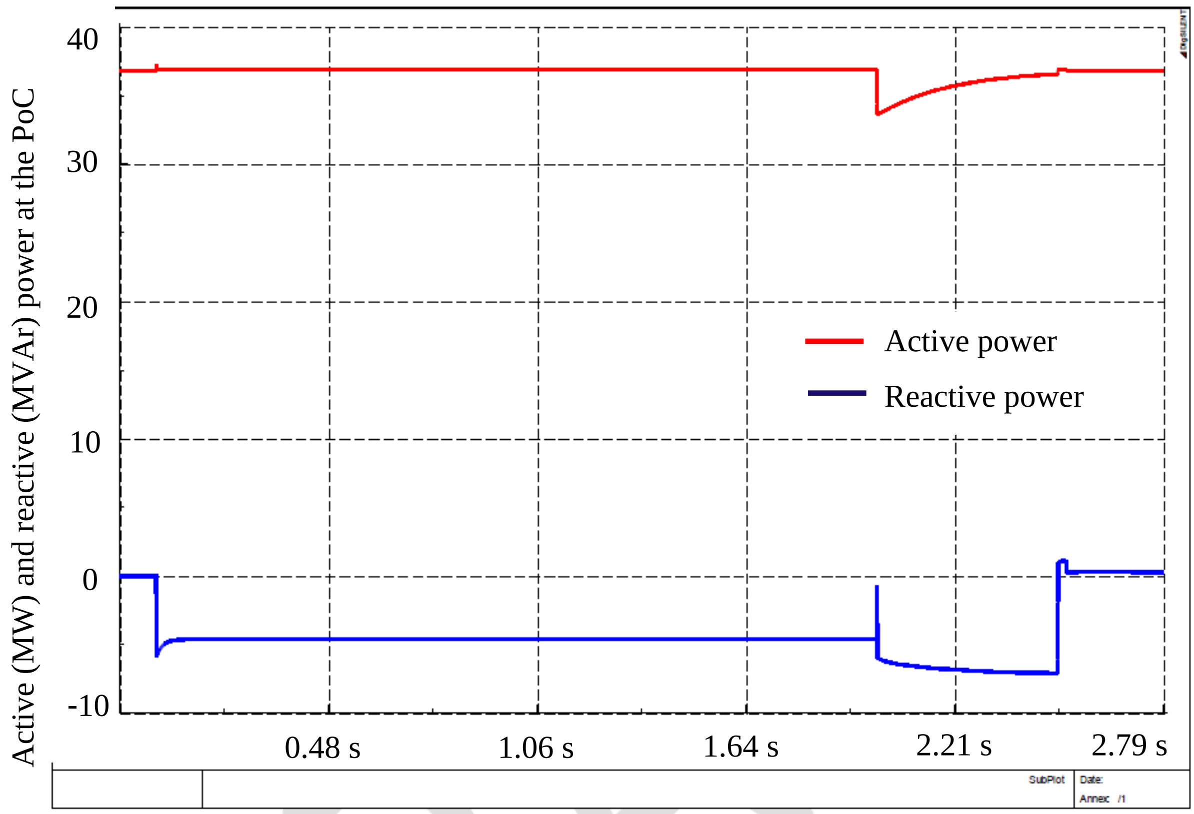

Figure 4-13: HVRT: active (red) and reactive (blue) power at PoC

Results from the high voltage ride through simulation are shown Figure 4-12 and Figure 4-13. When the voltage suddenly increases, the plant absorbs maximum reactive power in an attempt to lower the grid voltage. From the active power plotted, it is clear that the plant does not disconnect, but stays connected and absorbs the maximum amount of reactive power at the PoC in an attempt to lower the grid voltage.

4.2.4 Summary

When using the models provided by the PV developers, the facility passes all the tests subjected to. Thus based on the simulations the facility is grid code compliant with respect to LVRT and HVRT.

4.3 Supraharmonic simulations

Supraharmonics generated by the switching frequency of the inverters cannot be modelled with the current models supplied by the developers. Resonance points within the 132 kV sub-transmission network can be determined by performing a frequency sweep analysis under different network configurations to determine if this could coincide with the switching frequency of the PV inverters.

4.3.1 Network layout and description

A 64 MW PV facility was commissioned in 2015 connecting to Eskom's Soutdrift substation. It connects to a 132 kV sub-transmission network between a main transmission station (Harvard) and a main distribution substation, Virginia Terminal. WOLF conductor was used for backbone conductor.

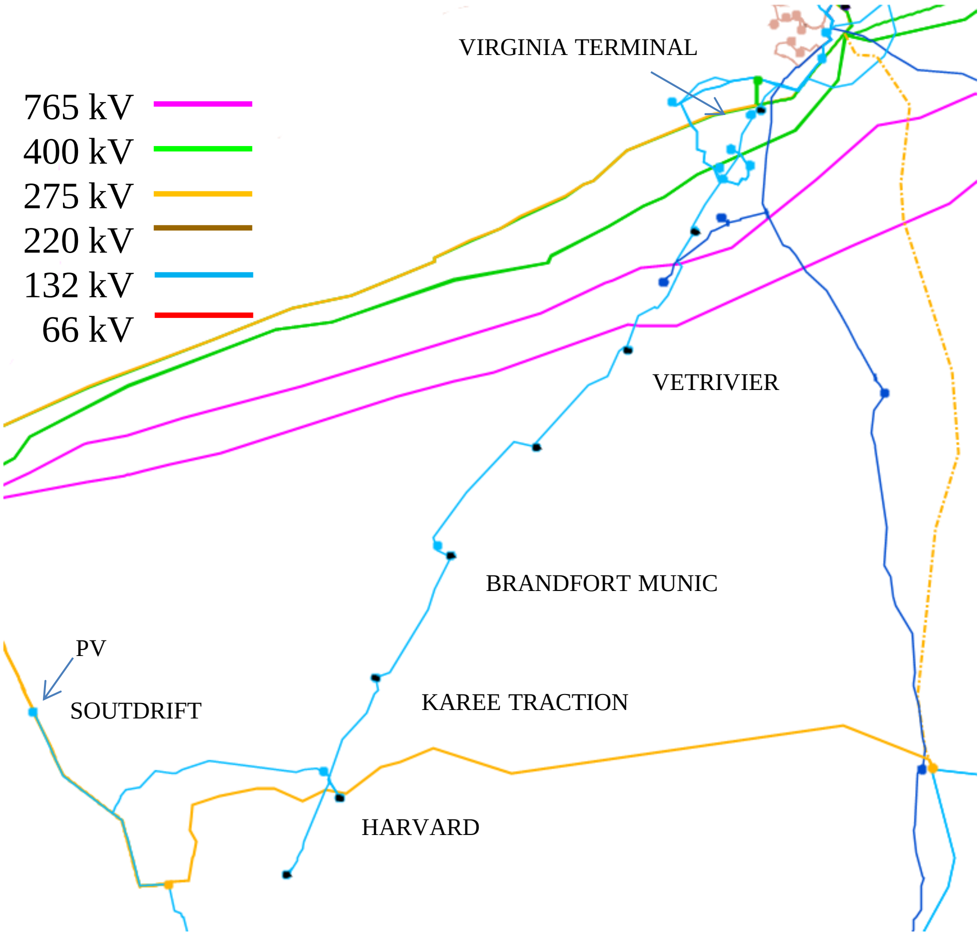

Figure 4-14: Geo layout of 132kV network between Harvard and Virginia Terminal

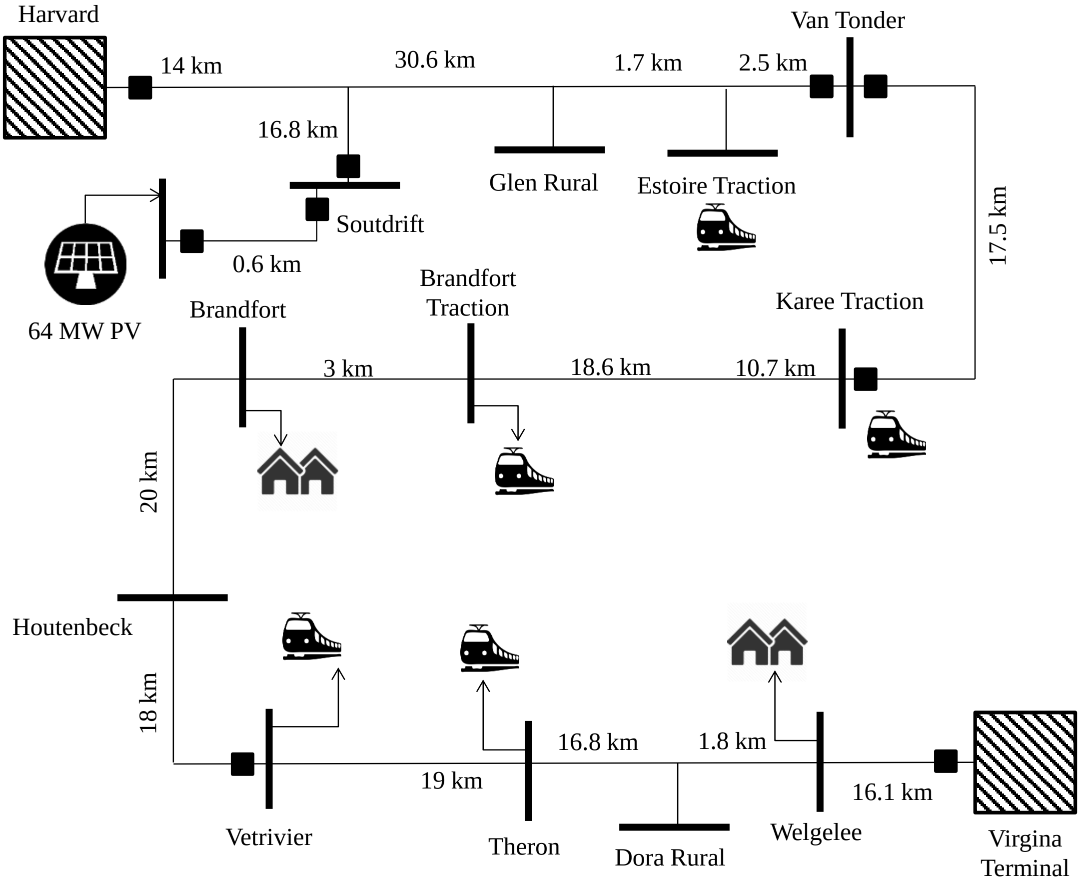

Figure 4-15: 132kV network between Harvard and Virginia Terminal

In order to simulate the network resonant points, the PowerFactory® network model was change in order to perform a harmonic sweep analysis as stipulated in Eskom's Guideline for Power quality simulations [54].

4.3.2 Network conditions

Simulations are done under normal grid conditions and by opening each source in turn to determine if this will move the network resonance point.

4.3.3 Simulation setup

A harmonic sweep analysis is performed under various conditions using PowerFactory®. The simulations done are summarized below in Table 4-10

Table 4-10: Harmonic sweep analysis

	Network
Simulation 1	Normal network conditions
Simulation 2	Harvard disconnected
Simulation 3	Virginia terminal disconnected

Figure 4-16 shows the harmonic resonance points under normal network conditions. Two prominent resonance points are identified at 2166 Hz (43 – 44th) with 5459 Ω and 2689 Hz (53 – 54th) with 5351 Ω.

The biggest concern is the resonance point at 2689 Hz as this coincides with the IGBT switching frequency of 2.67 kHz.

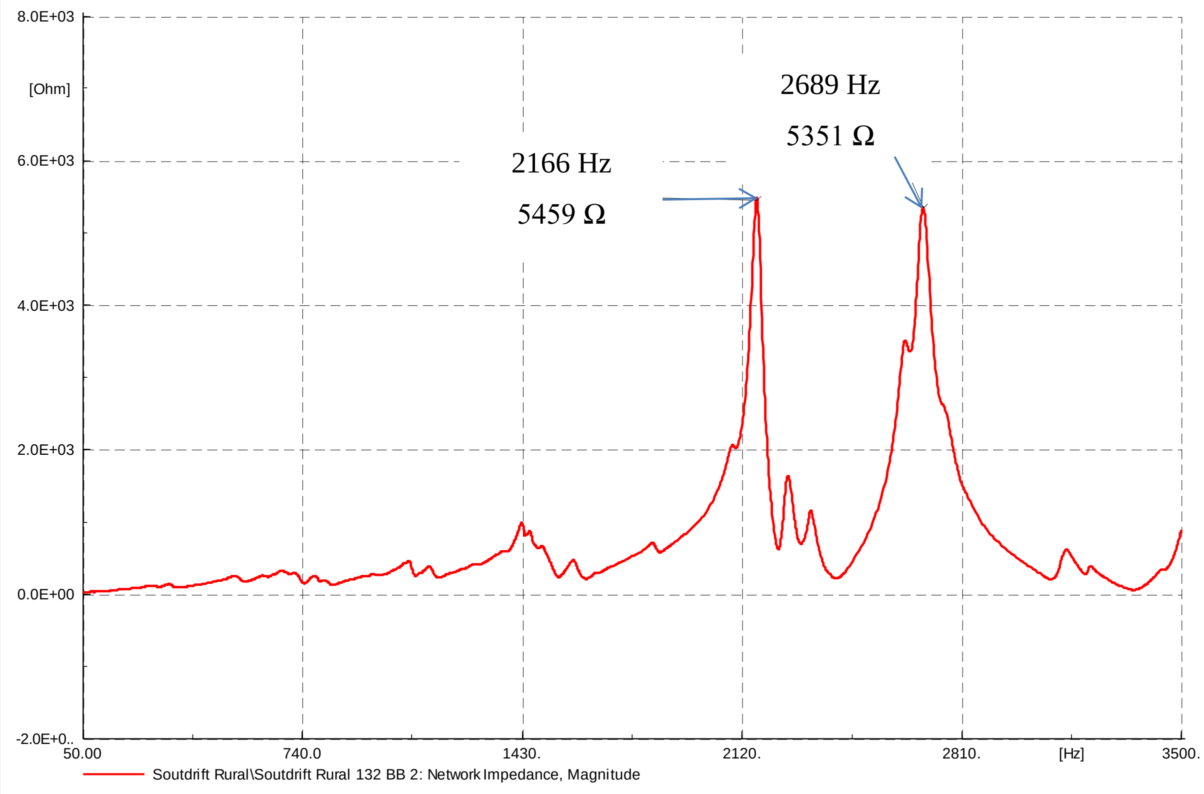

Figure 4-16: Simulation 1 – Normal network conditions

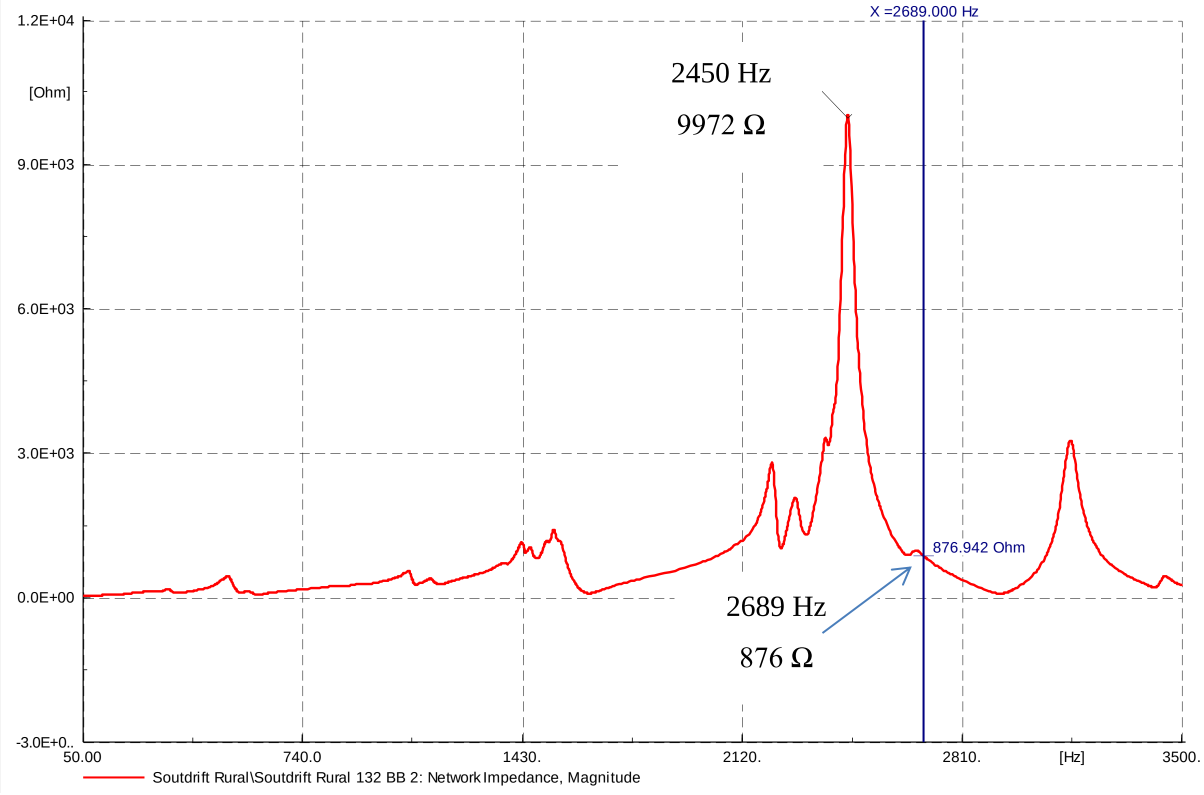

Figure 4-17: Simulation 2 – Virginia terminal network disconnected

When the 132kV Vetrivier – Houtenbeck breaker is opened and the harmonic sweep analysis is repeated, the resonance points move to 2450 Hz with 9972 Ω. The impedance of the potentially problematic frequency at 2689 Hz is reduced from 5351 Ω to 876 Ω.

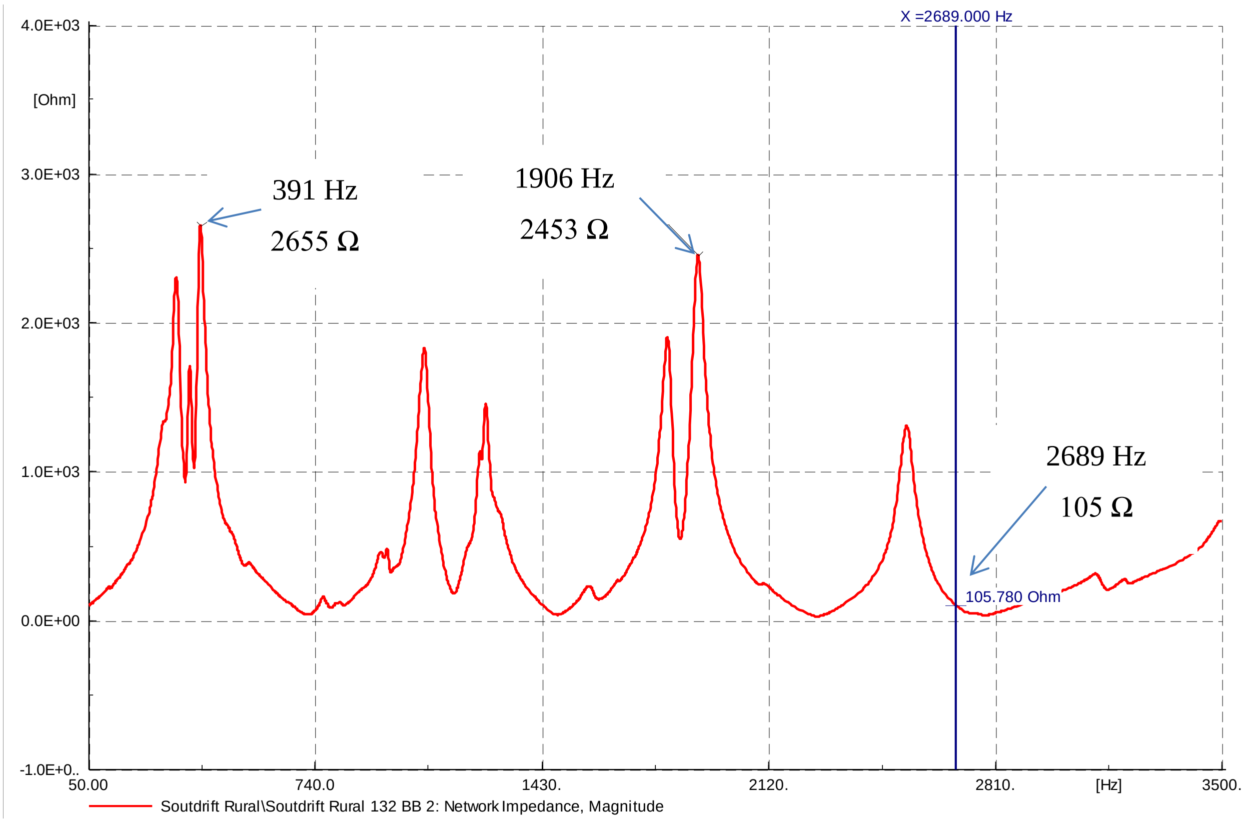

Figure 4-18: Simulation 3 – Harvard network disconnected

With the Harvard network disconnected as shown in Figure 4-18, the frequency sweep changes again with an even greater reduction at 2689 Hz to 105 Ω.

4.3.4 Network strengthening

An alternative is to build a new 132 kV sub transmission line between Harvard and Soutdrift. With this alternative, the network resonance point shifts to 2063 Hz and 2548 Hz as shown in Figure 4-19. The impedance at 2698 Hz is 909 Ω.

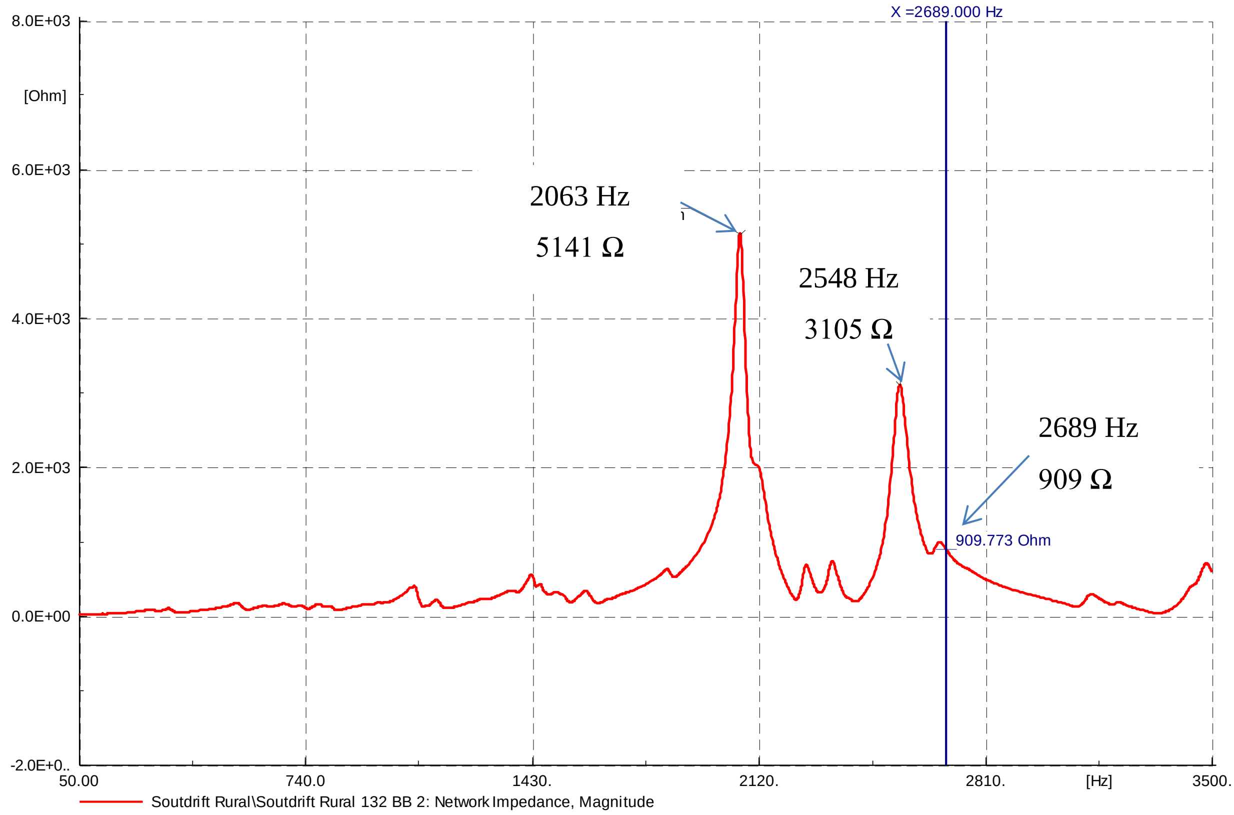

Figure 4-19: Additional 132 kV sub-transmission line

4.3.5 Summary

Harmonic sweeps for the network was simulated under various network conditions. As stated, present RE generation models are not adequate in calculating supraharmonics. But from the harmonic sweeps it is clear where the network resonance points are, under various operating conditions could overlap with the switching frequency of PV inverters.

4.4 Reactive power support simulations

PowerFactory® is used to determine if it is possible to support the network voltage by only using the reactive power component of RE generators during network contingencies. A specific network and RE generator, based on actual data is used to study the possibility.

4.4.1 Network layout and description

The network in question is a 132kV sub transmission network between Olien and Ferrum, located in the Northern Cape near Postmasburg. Figure 4-20 shows the geographic layout of the network and Figure 4-21 shows the schematic network layout. Network backbone is built with WOLF conductor with ratings shown in Table 4-11.

Table 4-11: WOLF conductor ratings

CONDUCTOR	RATE A	RATE B
WOLF	363 A (83 MVA @ 132 kV)	528 A (120 MVA @ 132 kV)

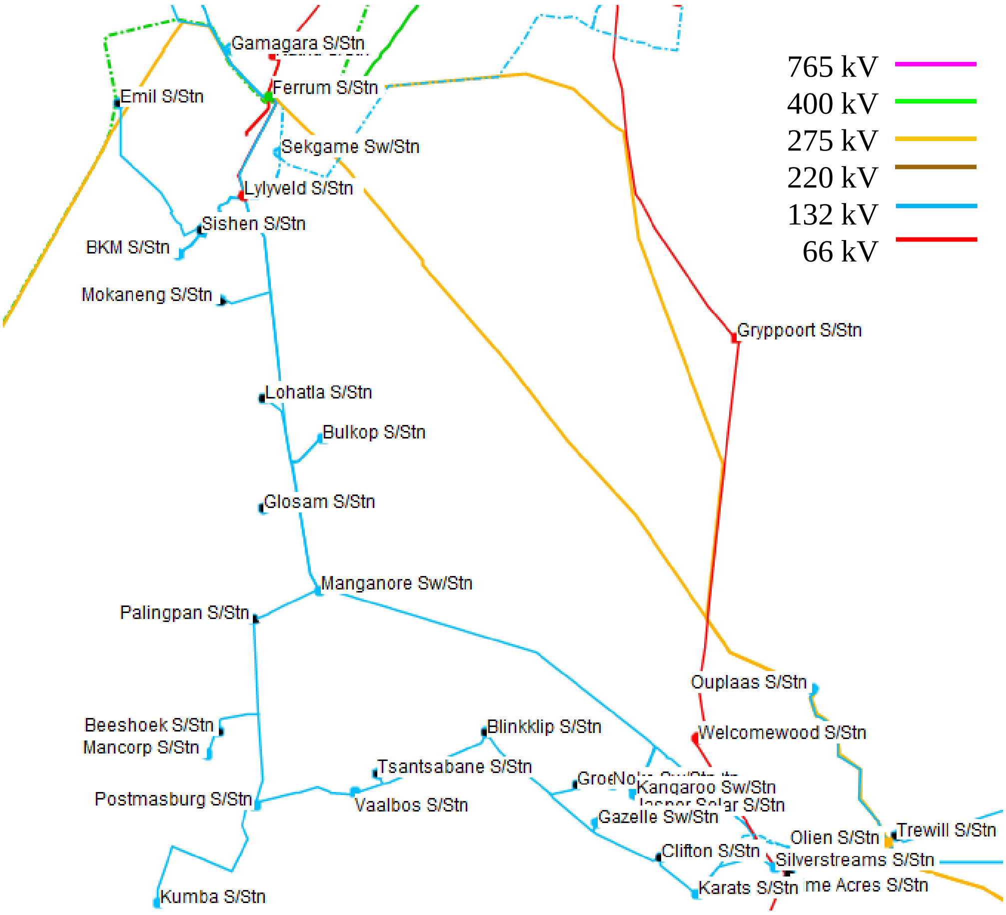

Figure 4-20: Geo layout of 132kV network between Olien and Ferrum

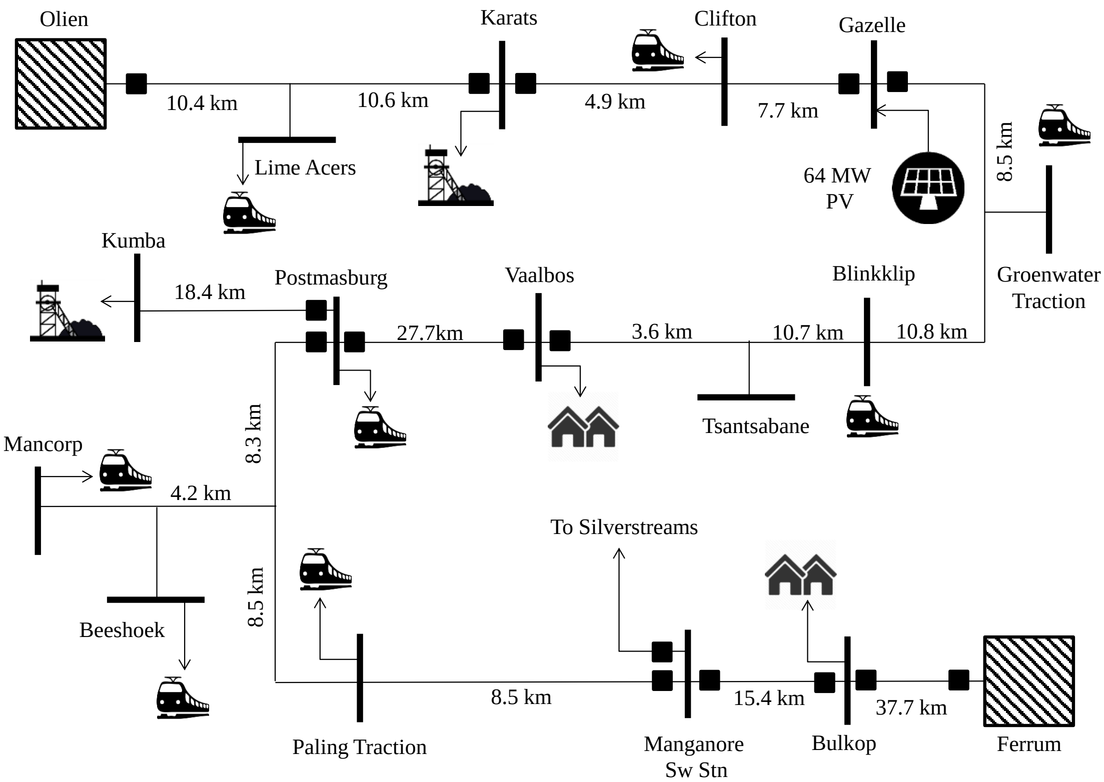

Figure 4-21: Schematic layout of 132kV network between Olien and Ferrum

4.4.2 Network loading and generation

Network loading consists of a mixture of mining, residential and 3 phase traction load. Total load on the network is shown in Figure 4-22. Comparing the load profiles of the total load (shown in Figure 4-22) and the mining load in Figure 4-23, it is clear that Karats mine is the biggest consumer of energy in the 132 kV network.

In 2015 a 64 MW PV facility was commissioned at the newly constructed Gazelle substation. As per grid code requirements the plant is able to supply or absorb 21 MVAr.

Figure 4-23 shows the yearly loading (2017) of Karats mine. The mine operates continuously for the duration of the year, with some reduction in load during maintenance. Figure 4-24 shows a typical weekly loading of the mine. Load varies between 31 and 49 MVA, but can still be seen as constantly high.

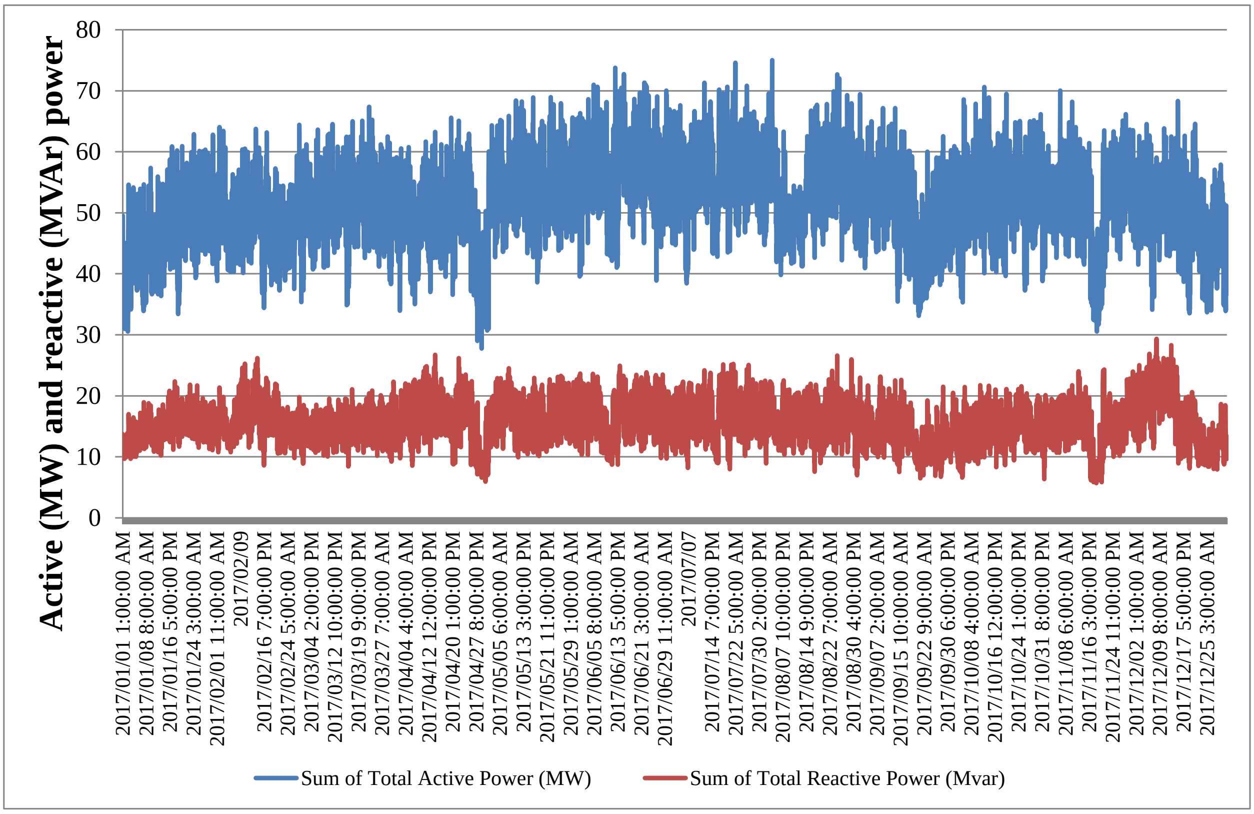

Figure 4-22: Total loading of 132 kV network 2017

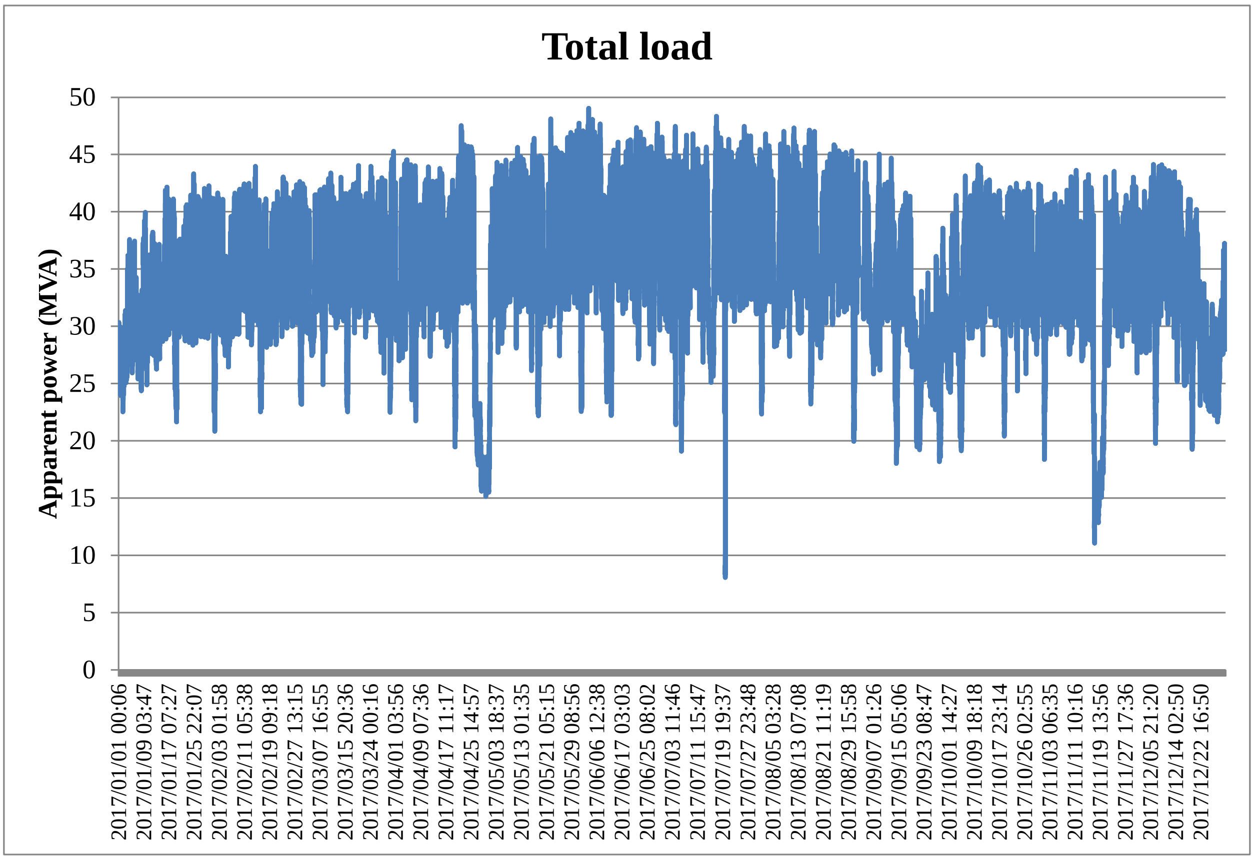

Figure 4-23: 2017 loading at Karats Mine

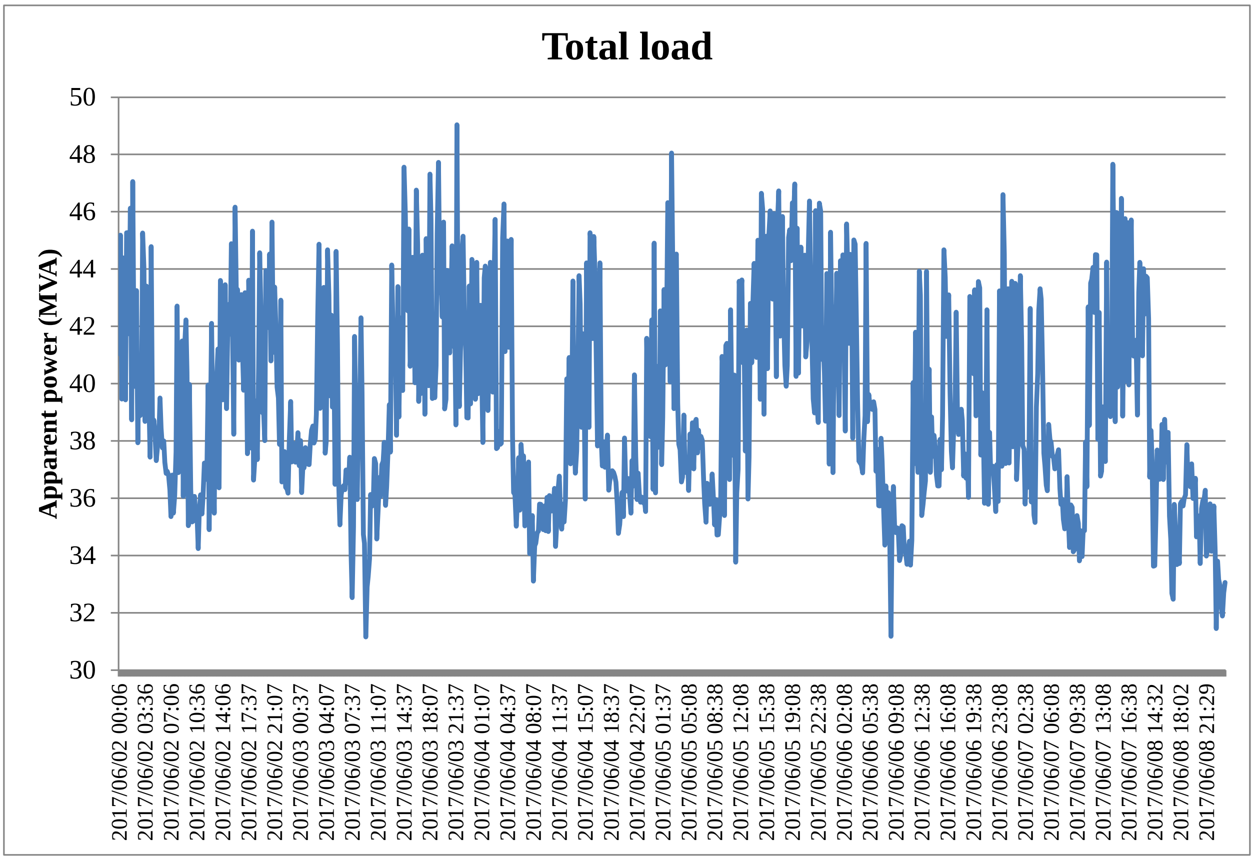

Figure 4-24: Weekly loading of Karats Mine

4.4.3 Network conditions

Normal network configuration is shown in Figure 4-21. Mining at Karats consumes the most energy. The critical network contingency would be to lose the connection to Olien, the load at Karats would have to be supplied from Ferrum, approximately 150 km away.

4.4.4 Simulation setup

Using the network models in PowerFactory® to calculate the fault levels and (7), the fault levels and SCR is calculated in shown in Table 4-12.

Table 4-12: Fault levels

	Fault level (MVA) Normal grid conditions	Fault level (MVA) Weak Grid conditions	Reduction in fault level
Gazelle	1297.7 MVA	436.9 MVA	66.33 %
Karats	1692.4 MVA	383.8 MVA	77.32 %

The SCR is calculated in shown in Table 4-13

Table 4-13: SCR under normal and weak grid conditions

Gazelle	Normal grid conditions	Weak Grid conditions
Fault level (MVA)	1297.7	436.9
Rated plant output (MVA)	64	64
SCR	20.27	6.82

As shown in [28], networks with a SCR of less than 10 is considered weak.

Various simulations were done with the 2017 peak load of the network with several generation scenarios and network contingencies to determine if the total load can be supplied whilst ensuring voltage regulation is maintained.

Table 4-14: Simulation scenarios

	Network	Generation
Simulation 1	Normal network conditions	No generation
Simulation 2	Olien network switched out	No generation
Simulation 3	Normal network conditions	RE generation in voltage control mode; Full active power output
Simulation 4	Olien network switched out	RE generation in voltage control mode; Full active power output
Simulation 5	Olien network switched out	Only reactive power support from RE generation; Zero active power output

Table 4-15: Simulation results

	Simulation 1	Simulation 2	Simulation 3	Simulation 4	Simulation 5
Name	Voltage (pu)	Voltage (pu)	Voltage (pu)	Voltage (pu)	Voltage (pu)
Olien 132 BB2	1.02	1.03	1.02	1.02	1.03
Karats 132 BB 1A	1.01	0.90	1.02	1.00	0.97
Clifton Traction 132 BB 1	1.01	0.91	1.02	1.00	0.98
Gazelle 132 BB 1B	1.01	0.91	1.03	1.01	0.98
Blinkklip Traction 132 BB 1	1.01	0.93	1.02	1.01	0.99
Tsantsabane Traction 132 BB 1	1.01	0.94	1.02	1.01	0.99
Vaalbos 132 BB 1	1.01	0.94	1.02	1.01	0.99
Postmasburg Traction 132 BB 1B	1.01	0.96	1.02	1.01	0.99
Palingpan Traction 132 BB1	1.02	0.98	1.02	1.02	1.01
Manganore 132 BB 1	1.02	1.00	1.02	1.02	1.01
Bulkop 132 BB 1	1.02	1.00	1.02	1.02	1.02
Ferrum 132 BB2S	1.02	1.02	1.02	1.02	1.02

Comparing simulation 1 and 2, it is clear that during the critical network contingency, the network unable to supply the required load and ensure effective voltage regulation. The network is not under a thermal constraint as the WOLF conductor is able to supply the load, but a voltage constraint. Exceeding the voltage limits under network contingencies as seen in Table 4-16. Normally, Karats mine would be instructed to reduce load during a network event that disconnected the grid from Olien or the maintenance of Eskom and the mine would be aligned to avoid production losses at the mine.

Table 4-16: HV voltage limits [18]

Normal Network conditions	± 5 %
n-1 conditions	± 7.5 %

Simulation 3 shows a voltage increase at the PoC. This is due to the injection of active power in the grid from the RE generation, but the voltage rise associated with the injected power is managed by the reactive power capability of the RE generator operating in voltage control mode.

With simulation 4 and 2, the same critical contingency is triggered, but the RE generation is regulating the grid voltage by injecting active and reactive power (in voltage control mode) as per the grid code requirements. This is a significant improvement compared to simulation 2. The benefit with the support from the RE generation is that the mine does not have to reduce load during a critical network condition. However, due to the intermitted nature of RE generation, the active power supplied to the network is not guaranteed.

Simulation 5 shows the network voltages if the RE generation would only supply reactive power to the grid, i.e. active power is not available (due to the weather), but the RE generation is still able to supply reactive power to the grid – providing an ancillary service with respect to voltage control.

Even during unfavourable environmental conditions, the RE generation (if able and allowed to provide an ancillary service) is able to keep the network voltage within acceptable limits.

4.4.5 Alternative

The only viable alternative to supply the required load to the mine within the network voltage limits, would be to build an alternative supply line to Kartas mine. In order to do this, the high level scope of work for such a project would be:

- Establish new 132 kV feeder bay at Olien substation
- Establish new 132 kV feeder bay at Karats substation
- Acquire servitude for the construction of a 132 kV sub transmission line
- Build ± 21 km 132 kV sub transmission line

This option is currently perused by Eskom at a planned cost of R45 mil (in 2017). It does provide advantages over the proposed reactive power compensation from RE generation in terms of increasing the fault level and increasing network reliability, but it comes at a huge capital investment.

4.4.6 Summary

From the simulations performed, the featured network is not compliant with voltage regulation under *n-1* conditions. Network strengthening would solve the problem, but this is a very expensive alternative. The proposed solution of using the reactive power support from the RE generation as an ancillary service, would be sufficient for voltage support during *n-1* conditions even when the RE generation does not export any active power.

CHAPTER 5 VALIDATION

The operational risks identified in chapter 3 were verified with simulations in chapter 4. Actual measurements obtained from various sources are now used as validation of the identified operational risks.

5.1 Data sources

Various data sources are used to reconstruct events associated with the identified operational risks. The data sources are listed below.

5.1.1 Elspec Blackbox® recordings

Elspec Blackbox® G4500 is a Class A recorder, used to monitor different RE generation sites. It features continuous waveform recording and monitoring capabilities stipulated in IEC 61000-4-30 edition 2.

5.1.2 Eskom SCADA system

Alarms and analogues are provided by Eskom's SCADA system. Analogues (active power, reactive power, current and voltage) are also stored as 10 min averaged values. Only one phase to phase voltage is available (normally white to blue phase, but can be any other phases depending on the installation). Positive or negative values on the current, active and reactive power indicated the direction of power flow.

5.1.3 Eskom MV90 metering database

MV90 metering database is statistical and/or metering data for billing purposes, consisting of either 2 or 4 quadrant metering data (depending on the installation requirements). Data is collected from the CT and VT metering circuits. Main and check metering is used with two separate meters gathering data from separated CT and VT cores. Active and reactive power (as needed for billing purposes) is stored as 30 min averaged values.

5.2 Renewable energy generation connected to sub-transmission traction networks

A 5 day system event represents the critical network contingency. The data obtained during this event will be used to further analyse the effect voltage unbalance has on RE generation.

5.2.1 Measurement sources

An Elspec Blackbox® was installed at the PoC of the WEF at Panther substation. The logger was connected to the busbar VT's and feeder CT's. Analogue data and operating logs from the SCADA system were used to reconstruct the system events.

5.2.2 Description of events

An outage was requested from 1 – 5 December 2016 in order to connect two new 132 kV lines to the newly extended 132 kV busbar at Hydra MTS. In order to accommodate the construction work, the closing spans of 132 kV Hydra – Bletterman was disconnected. This specific outage scenario represents the weak grid condition for the network.

The outage started on 1 Dec 2016 at 06:00 with the opening of the 132 kV Hydra – Bletterman breaker and ended on 5 Dec 2016 at 19:32.

Table 5-1: Outage start and end date

	ALARM_TIME1	ALARM_TYPE_DISP	DESCRIPTION
START	01/12/2016 06:00:17.769	IND	Hydra TX Bletterman 1 132kV 132kV Bkr OPENED - Tele Control
END	05/12/2016 19:32:59.330	IND	Hydra TX Bletterman 1 132kV 132kV Bkr CLOSED - Tele Control

5.2.3 Voltage unbalance recordings

During normal grid conditions the recorded voltage regulation and unbalance is displayed in Figure 5-1 and Figure 5-2 respectively. Displayed data is a 90 min period during high generation output and typical loading under normal grid conditions.

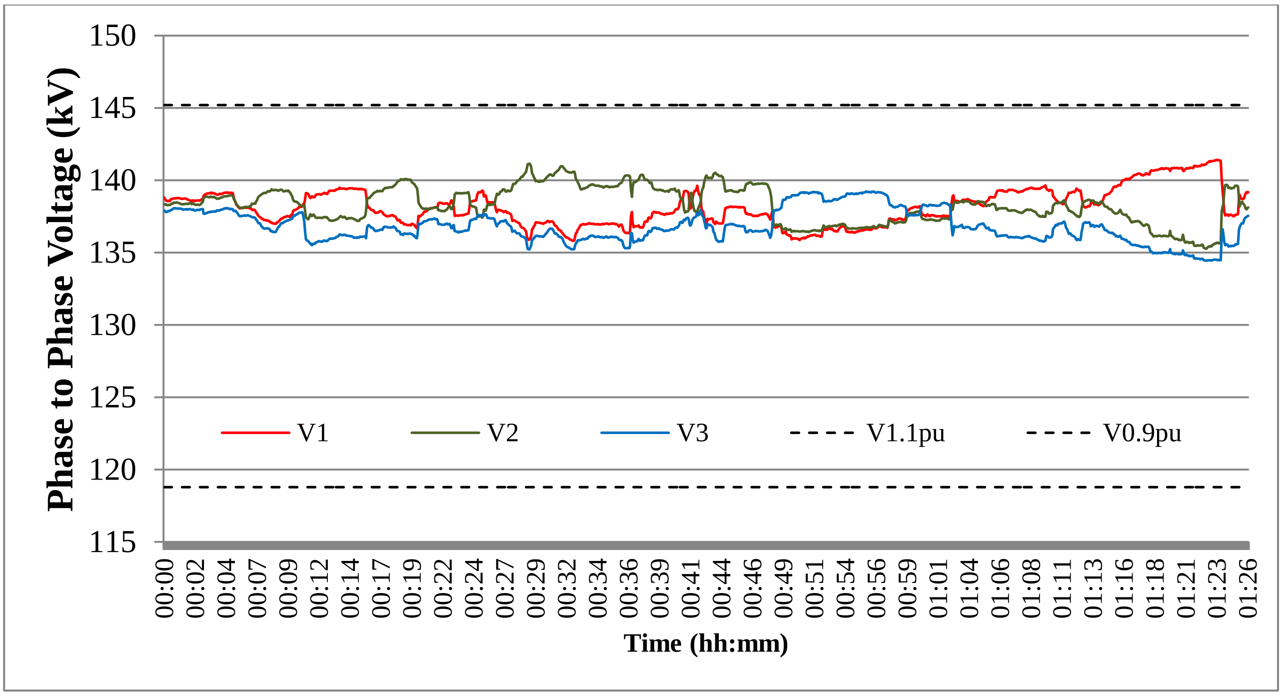

Figure 5-1: Phase to phase voltage regulation: Normal grid conditions

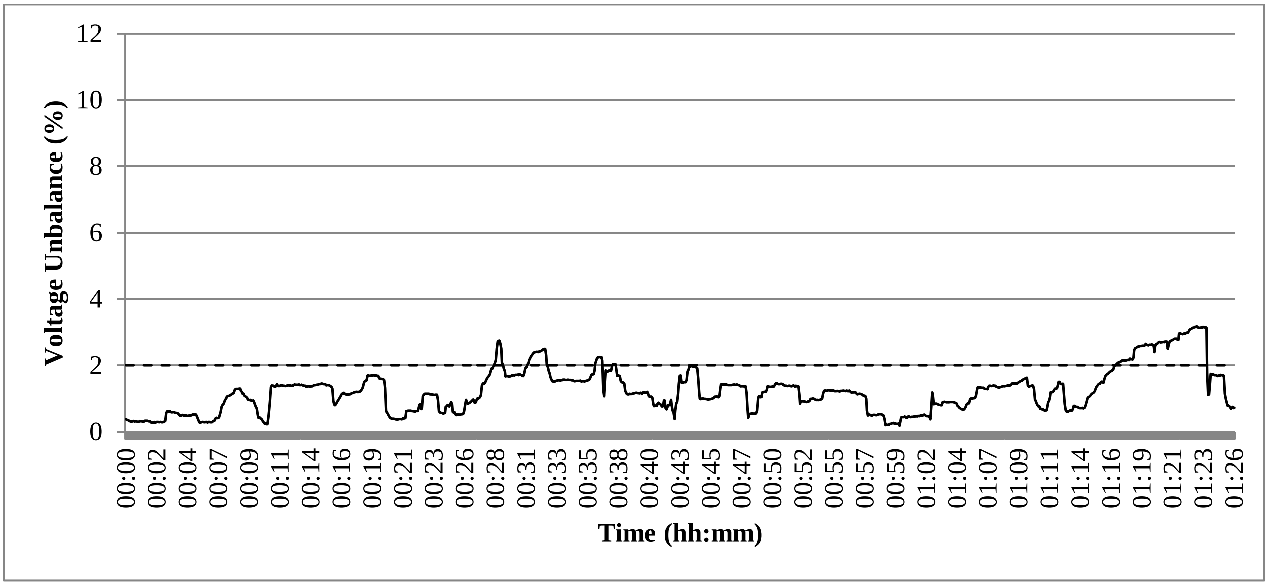

Figure 5-2: Voltage unbalance: Normal grid conditions

During *n-1* conditions, under similar generation and network loading conditions as in Figure 5-1 and Figure 5-2, the voltage regulation and voltage unbalance is plotted in Figure 5-3 and Figure 5-4.

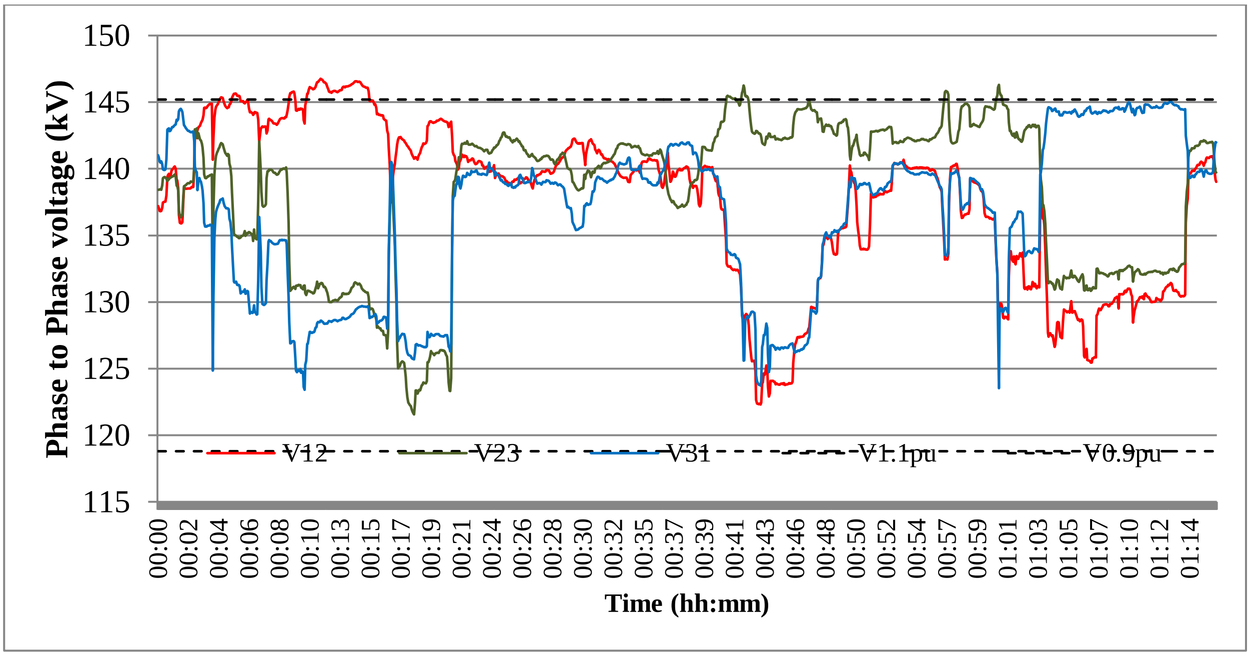

Figure 5-3: Phase to phase voltage regulation: Weak grid conditions

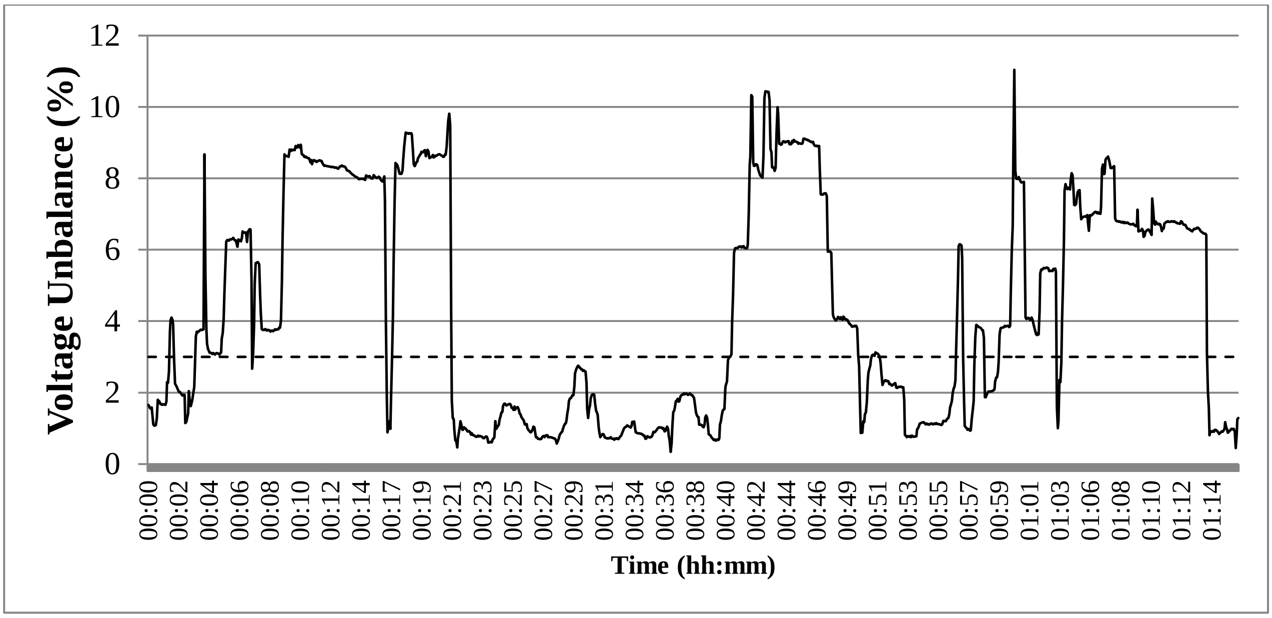

Figure 5-4: Voltage unbalance: Weak grid conditions

A significant increase in voltage unbalance is recorded and general lack of voltage regulation. The increase in voltage unbalance is a direct result of a reduction of fault level, which occurs when the weak grid condition is realized. An immediate increase in voltage unbalance is shown in Figure 5-5 at 06:00 when then breaker was opened resulting in the critical contingency.

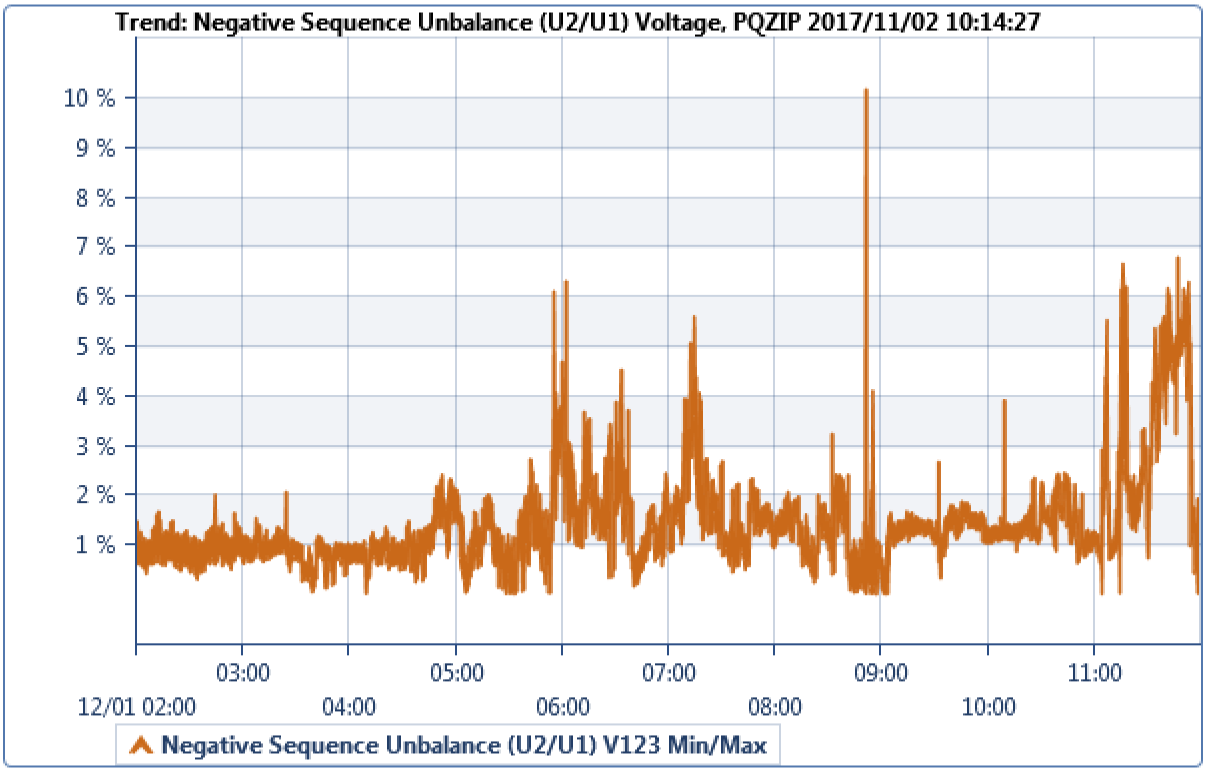

Figure 5-5: Voltage unbalance

It should also be noted that the voltage unbalance is not constant, but varies greatly over time. This is due to the intermitted nature of traction loads. Traction load is dependant of the direction of travel, elevation of the trajectory and frequency of trains passing. Figure 5-3 also shows how the traction load is shifted between phases. At first the single phase load is connected between the blue and white phases. Later on it shifts to red and blue and then to red and white. This confirms the inherent load balancing described in section 2.6.3.4.

5.2.4 Voltage control during weak grid conditions

Voltage control is based on regulating the PoC voltage by means of controlling the amount of reactive power injected or absorbed by the RE generator. Voltage control set point is defined by the NSP and implemented via SCADA by the DSO. Both the PV and wind facility is operating in voltage control mode as recommended by the simulations conducted in section 4.1.6.1.

The difference between the voltage control set point and the actual measured voltage, determines the amount and direction of the reactive power flow. Thus if the measured voltage is higher than the set voltage the facility will absorb reactive power in an attempt to lower the voltage to the voltage control set point. Should the measured voltage be lower than the set voltage the facility will inject reactive power into in the grid in order to increase the voltage to the voltage control set point. However, during weak grid conditions, the effect of active and reactive power on the voltage is much more profound as see with the power voltage curve simulations. A small change in reactive power can now cause a bigger than expected effect on the grid voltage. In Figure 5-6 the wind facility is generating 35 MW and operating in voltage control mode. Before the wind facility trips, the reactive power starts oscillating, creating a voltage oscillation.

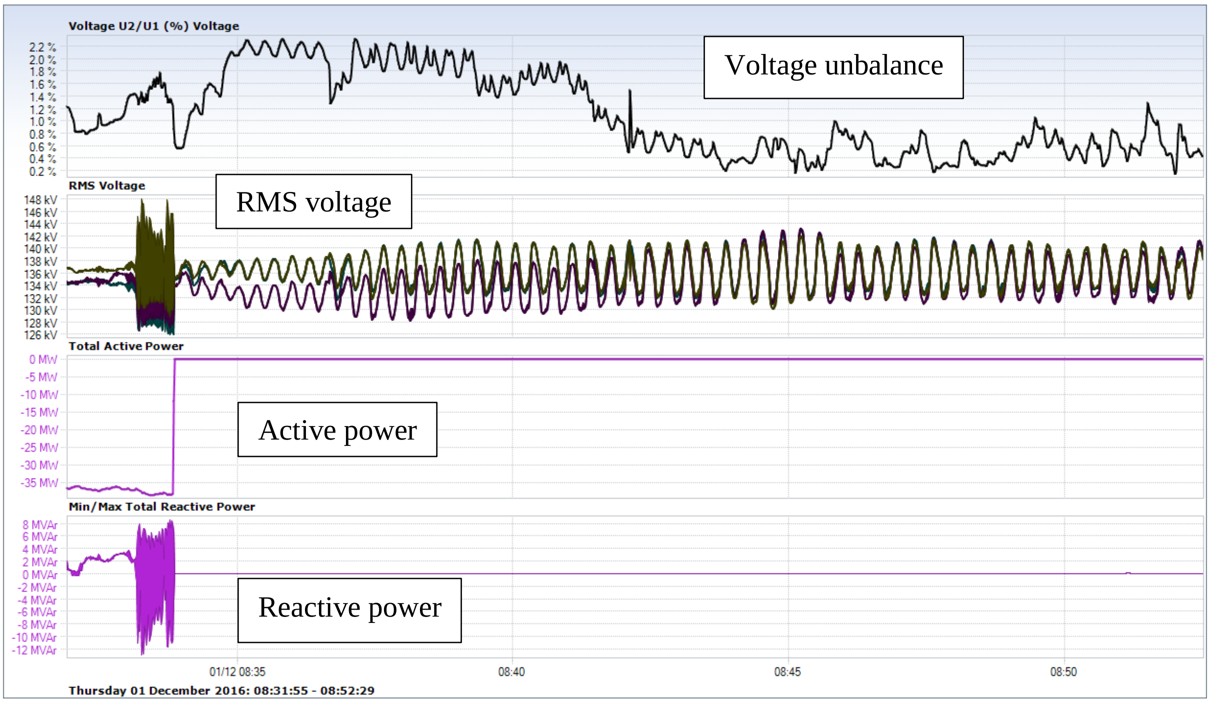

Figure 5-6: Voltage oscillations

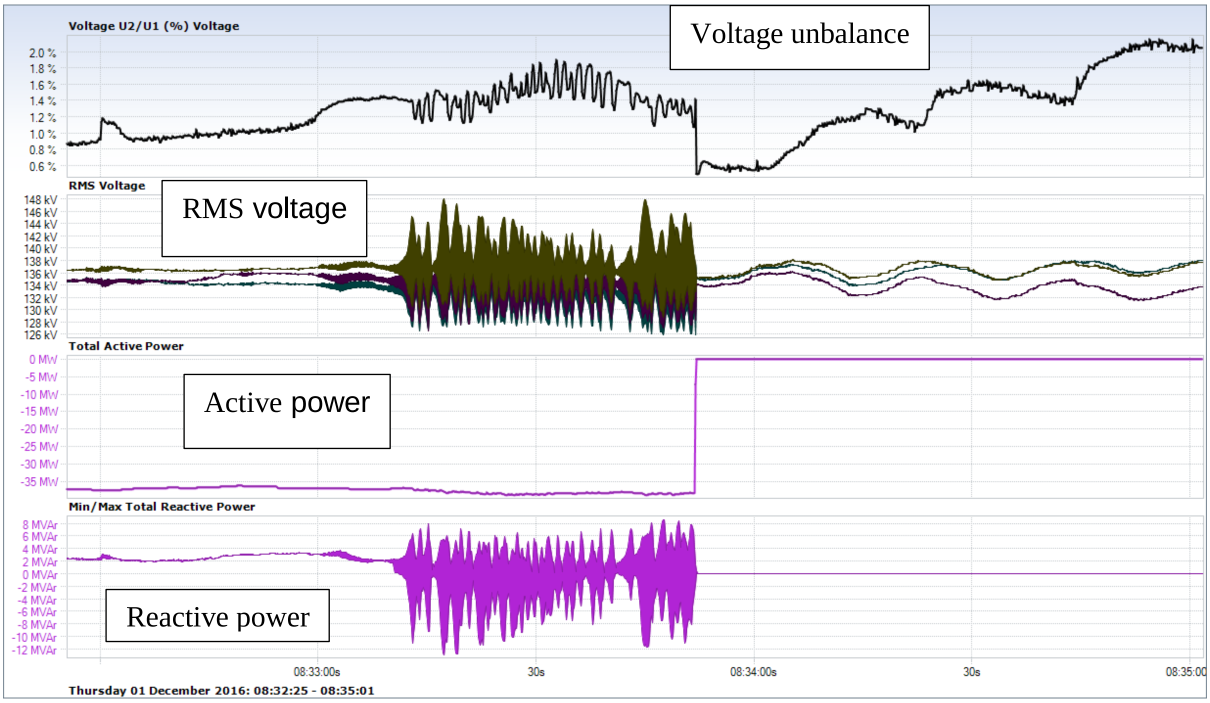

Figure 5-7: Detailed view of voltage oscillations

Figure 5-7 shows a zoomed-in version of Figure 5-6, before the facility trips. Active power output of the wind facility is stable at 35 MW, but the reactive power oscillates between 8 and -12 MVAr which causes the voltage oscillations. Even after the wind facility trips, the voltage oscillation continuous at a different frequency (better seen in Figure 5-6). This is due to the PV facility on the network still operating in voltage control mode.

This confirms that the RE generators cannot continue to operate in voltage control during the weak grid condition.

5.2.5 RE generation disconnections during network contingency

During the 5 day outage period both the PV and wind facilities tripped several times even after intervention from the DSO.

5.2.5.1 WEF disconnections

The wind facility tripped 15 times. A summary of the trips are shown in Table 5-2. Active and reactive power output of the plant is shown in Figure 5-8.

Table 5-2: WEF disconnections

#	Time	Alarm message	Cause
1	01/12/2016 08:37:43.033	Trfr1 HV Back Up Protection Sel751	ROCOF
2	01/12/2016 15:14:38.149	Trfr1 HV Back Up Protection Sel751	ROCOF
3	01/12/2016 17:14:36.172	Trfr1 Over/Under Voltage Trip Alarm	Under voltage
4	01/12/2016 21:27:43.277	Trfr1 Over/Under Voltage Trip Alarm	Over voltage
5	01/12/2016 23:02:12.948	Trfr1 Over/Under Voltage Trip Alarm	Over voltage
6	01/12/2016 23:28:15.450	Trfr1 Over/Under Voltage Trip Alarm	Over voltage

7	01/12/2016 23:40:53.652	Trfr1 Protection Not Healthy Alarm	Unknown
8	01/12/2016 23:56:24.450	Trfr1 Over/Under Voltage Trip Alarm	MV tapchanger
9	02/12/2016 07:10:07.306	Trfr1 Over/Under Voltage Trip Alarm	MV tapchanger
10	02/12/2016 07:35:03.319	Trfr1 Over/Under Voltage Trip Alarm	MV tapchanger
11	02/12/2016 12:17:08.831	Trfr1 Over/Under Voltage Trip Alarm	Under voltage
12	03/12/2016 16:55:41.016	Trfr1 Over/Under Voltage Trip Alarm	Over voltage
13	03/12/2016 19:53:25.401	Trfr1 Over/Under Voltage Trip Alarm	Over voltage
14	04/12/2016 23:29:39.431	Trfr1 Over/Under Voltage Trip Alarm	Over voltage
15	05/12/2016 06:43:47.828	Trfr1 Protection Not Healthy Alarm	Unknown

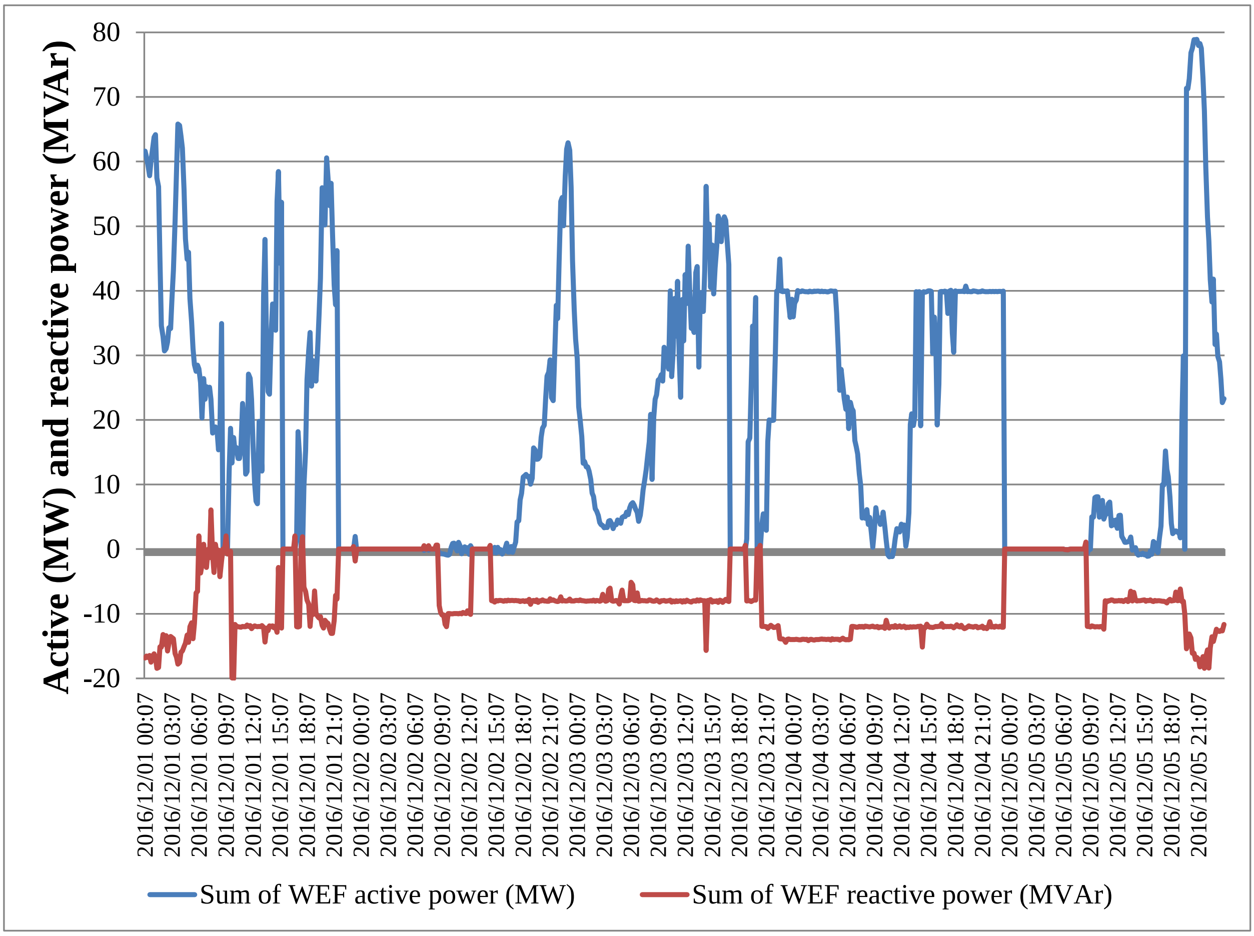

Figure 5-8: WEF: Active and reactive power during outage

5.2.5.2 PV facility disconnections

Table 5-3 summarizes the disconnections experienced by the PV facility during the network contingency. Active and reactive power output of the PV facility is shown in Figure 5-9.

Table 5-3: PV disconnections

#	ALARM_TIME	ALARM_MESSAGE	ALARM_TEXT
1	01/12/2016 15:32:31.805	Trfr1 132kV Bkr	TRIPPED
	01/12/2016 15:32:54.341	Trfr2 132kV Bkr	TRIPPED
2	01/12/2016 16:00:40.820	Trfr2 132kV Bkr	TRIPPED
	01/12/2016 16:00:40.994	Trfr1 132kV Bkr	TRIPPED
3	01/12/2016 16:29:35.135	Trfr1 132kV Bkr	TRIPPED
4	01/12/2016 17:14:03.463	Trfr1 132kV Bkr	TRIPPED
5	01/12/2016 22:34:13.843	Trfr1 132kV Bkr	TRIPPED
	01/12/2016 22:34:39.757	Trfr2 132kV Bkr	TRIPPED
6	02/12/2016 07:10:01.172	Trfr2 132kV Bkr	TRIPPED
	02/12/2016 07:10:01.486	Trfr1 132kV Bkr	TRIPPED
7	02/12/2016 11:53:36.894	Trfr1 132kV Bkr	TRIPPED
	02/12/2016 11:53:37.117	Trfr2 132kV Bkr	TRIPPED
8	02/12/2016 12:12:34.329	Trfr1 132kV Bkr	TRIPPED
9	02/12/2016 12:51:23.693	Trfr1 132kV Bkr	TRIPPED
10	02/12/2016 13:07:10.971	Trfr1 132kV Bkr	TRIPPED
11	02/12/2016 13:14:09.662	Trfr2 132kV Bkr	TRIPPED
12	02/12/2016 13:24:58.597	Trfr2 132kV Bkr	TRIPPED
13	02/12/2016 18:43:06.205	Trfr2 132kV Bkr	TRIPPED
	02/12/2016 18:43:06.212	Trfr1 132kV Bkr	TRIPPED
14	03/12/2016 06:11:42.969	Trfr1 132kV Bkr	TRIPPED
15	03/12/2016 19:57:17.027	Trfr1 132kV Bkr	TRIPPED
	03/12/2016 19:57:17.037	Trfr2 132kV Bkr	TRIPPED
16	04/12/2016 07:04:19.975	Trfr2 132kV Bkr	TRIPPED
	04/12/2016 07:04:19.978	Trfr1 132kV Bkr	TRIPPED
17	04/12/2016 07:25:52.330	Trfr1 132kV Bkr	TRIPPED
	04/12/2016 07:25:52.336	Trfr2 132kV Bkr	TRIPPED
18	04/12/2016 07:33:22.498	Trfr2 132kV Bkr	TRIPPED
19	04/12/2016 09:44:33.419	Trfr1 132kV Bkr	TRIPPED
	04/12/2016 09:44:33.429	Trfr2 132kV Bkr	TRIPPED
20	04/12/2016 10:21:09.107	Trfr2 132kV Bkr	TRIPPED
	04/12/2016 10:21:09.308	Trfr1 132kV Bkr	TRIPPED
21	04/12/2016 19:14:58.807	Trfr1 132kV Bkr	TRIPPED
	04/12/2016 19:14:59.025	Trfr2 132kV Bkr	TRIPPED

22	05/12/2016 09:46:12.688	Trfr2 132kV Bkr	TRIPPED
	05/12/2016 09:46:16.445	Trfr1 132kV Bkr	TRIPPED
23	05/12/2016 16:58:36.501	Trfr1 132kV Bkr	TRIPPED
	05/12/2016 16:58:38.472	Trfr2 132kV Bkr	TRIPPED
24	05/12/2016 18:32:12.117	Trfr1 132kV Bkr	TRIPPED
	05/12/2016 18:32:12.352	Trfr2 132kV Bkr	TRIPPED

The PV facility does not have the same level of detail on the alarms received at Eskom's Bloemfontein DSO centre as the WEF as it was commissioned two years before the PV facility. It does not incorporate the latest standard for SCADA interface signals.

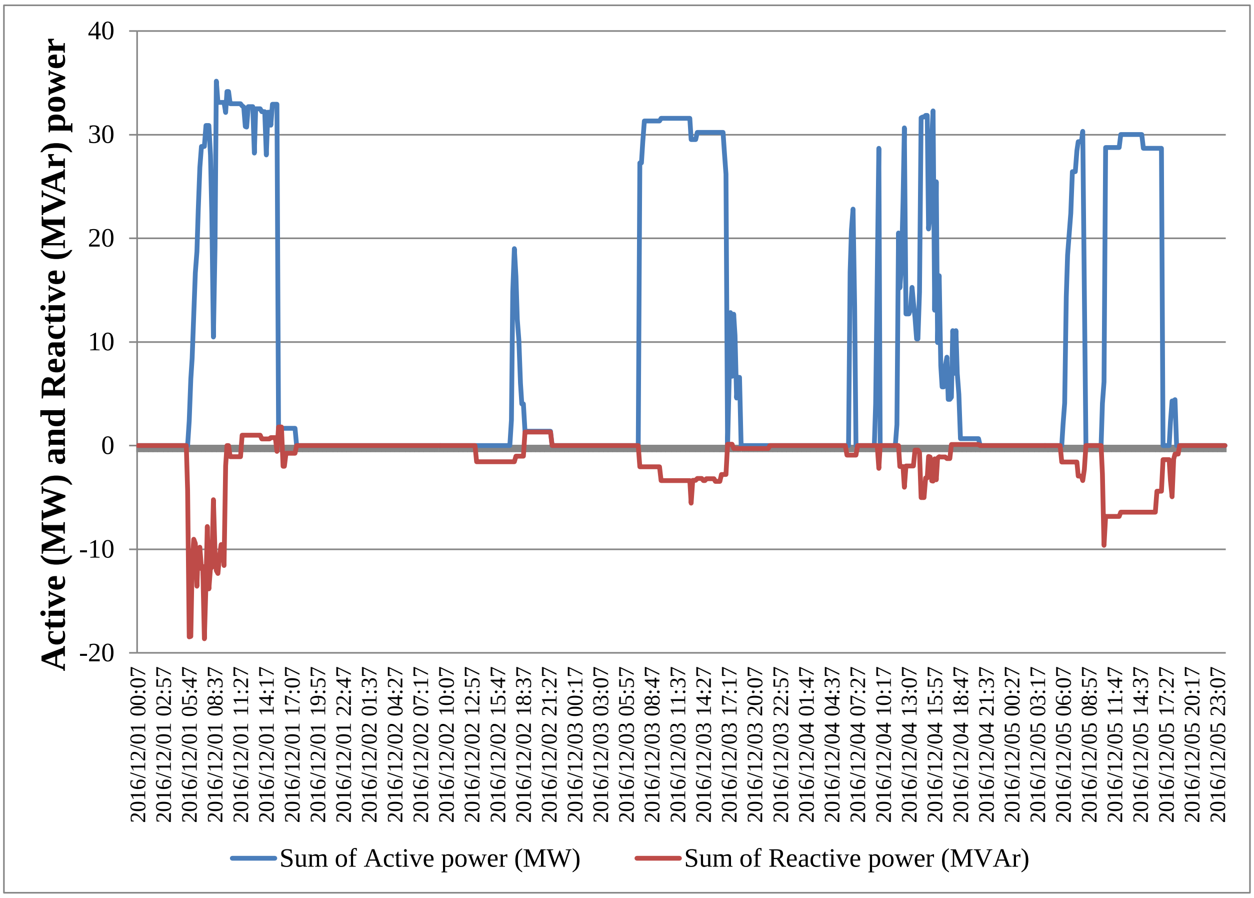

Figure 5-9: PV active and reactive power output during the network contingency

5.2.6 Detailed events

Some of the events described above are analysed in detail below. This shows how the DSO failed to manage the grid voltage under unbalanced conditions resulting in tripping of the RE facility on either under or over voltage. During this time, the WEF was operating in constant Q mode with the DSO applying set points as needed.

5.2.6.1 WEF event no.3: Under voltage trip

At the time of the trip, the PV facility was already disconnected from the grid as seen in the graphs above. The WEF tripped on under voltage whilst operating in constant Q mode with reactive power set point of -12 MVAr. The RE generator should absorb 12 MVAr.

The graphs below indicate:

- Active power generated was 16 MW
- Reactive power absorbed was 12 MVAr
- Only one phase was low enough to qualify for a LVRT disconnection
- Voltage unbalance was 10 % and increasing
- After the trip, the voltage on the white phase increased with 8 kV, due to the fact that the reactive power absorbed by the WEF was no longer available.

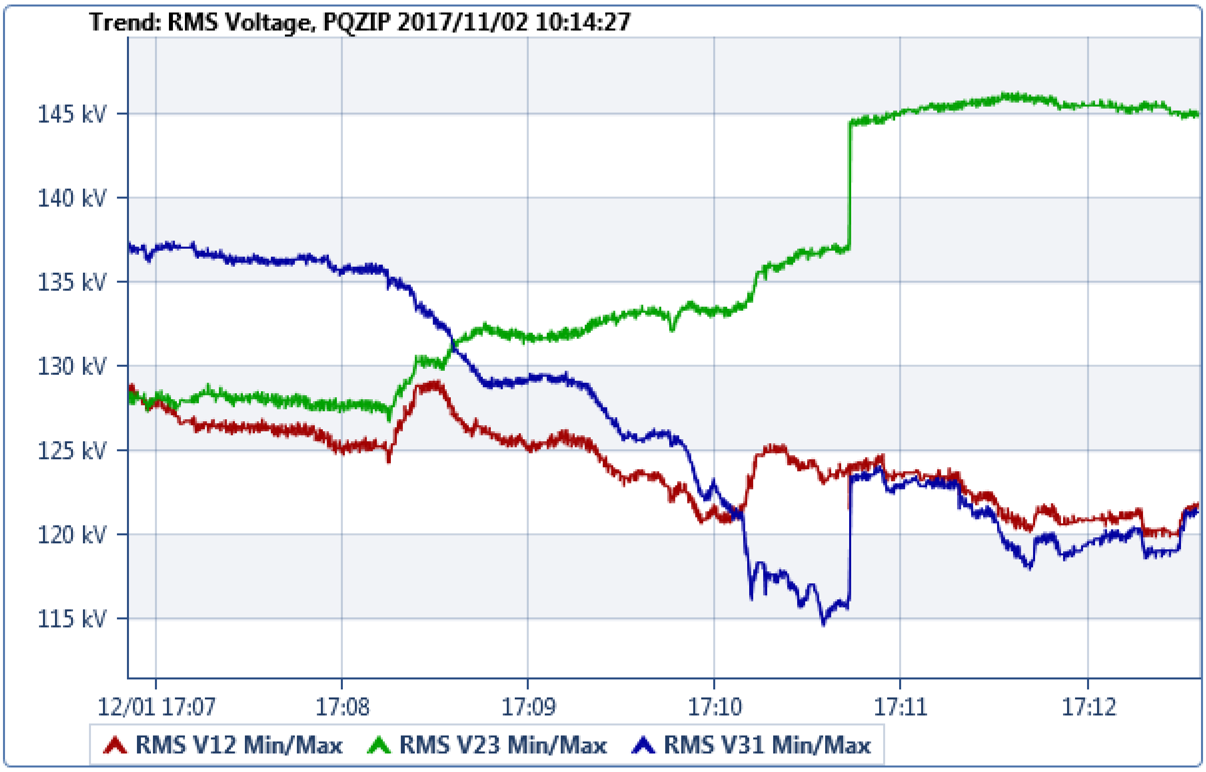

Figure 5-10: WEF under voltage event no.3: three phase Line to line voltage

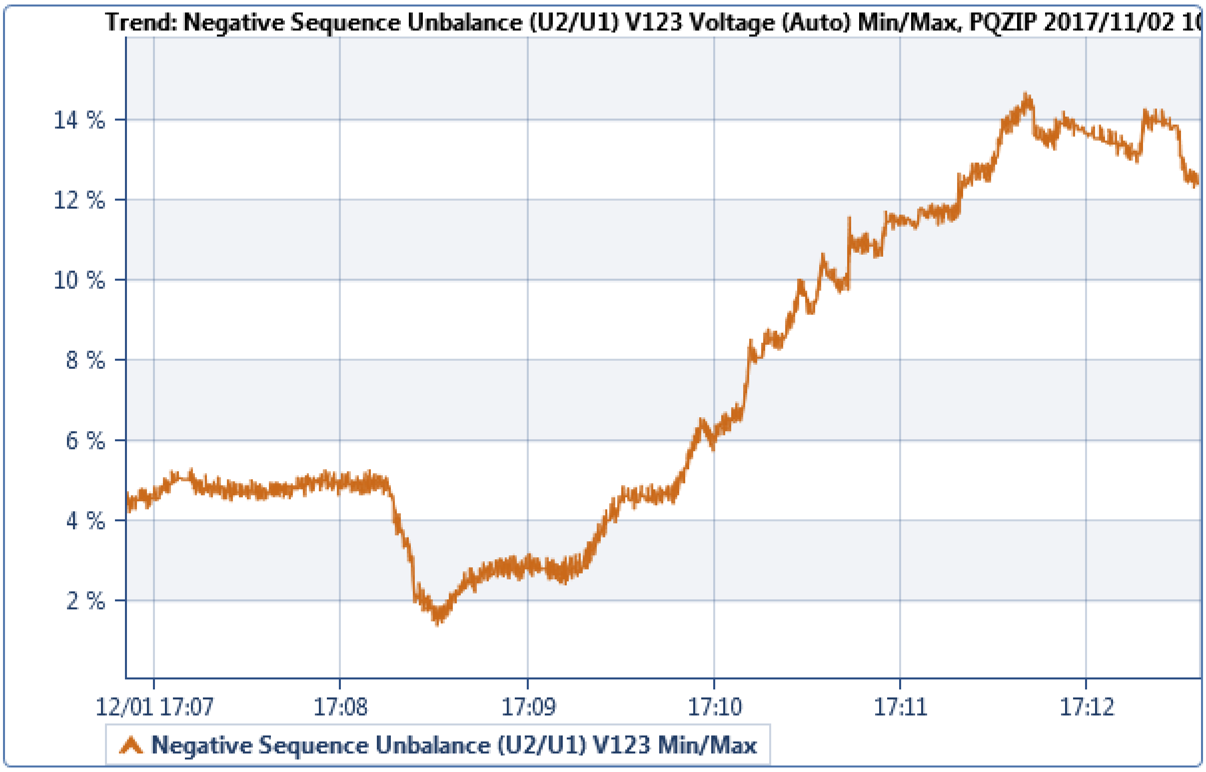

Figure 5-11: WEF under voltage event no.3: voltage unbalance

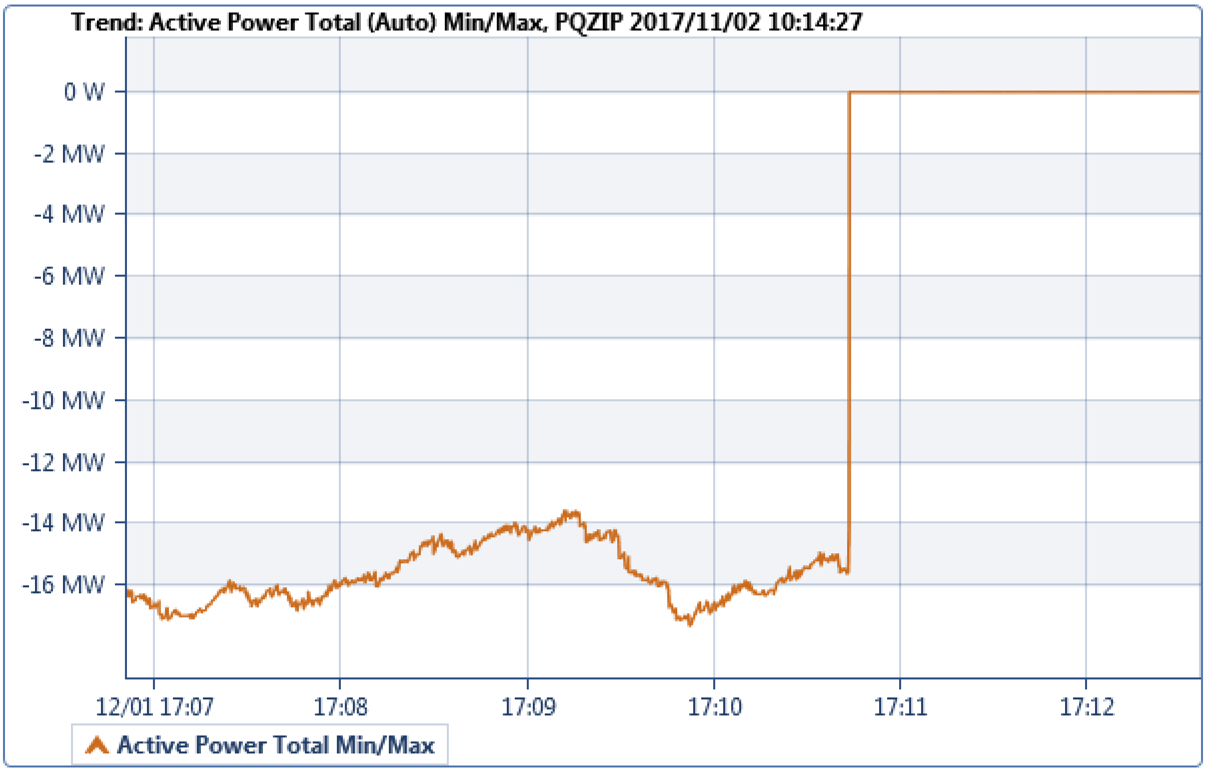

Figure 5-12: WEF under voltage event no.3: Total active power

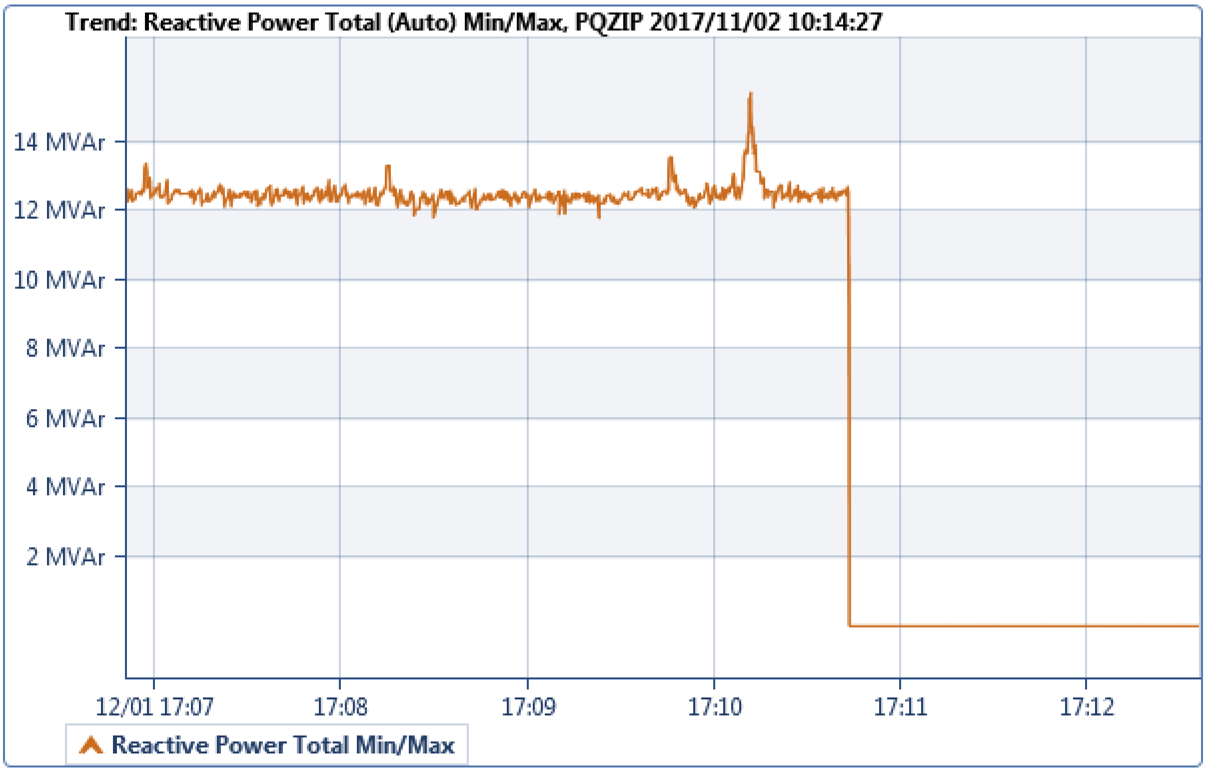

Figure 5-13: WEF under voltage event no.3: Total reactive power

Because of the severe voltage unbalance it becomes very difficult to determine an appropriate Q control set point. With the low amounts of active power output (16 MW), the amount of reactive power absorbed was too much and the plant tripped on under voltage. But since the voltage on the white phase increased to above 145.2 kV (the 10 % upper limit) after the WEF disconnected, there was also a risk of tripping the plant on over voltage if enough wasn't absorbed.

5.2.6.2 WEF event no.4: Over voltage trip

During event no.4 the WEF tripped on over voltage whilst operating in constant Q mode with a -13 MVAr set point. No contribution from the PV facility since this event occurred at night. The following is noted on the graphs below:

- Active power generation was 56 MW
- Reactive power absorption was 13 MVAr
- Only one phase qualified for a HVRT disconnection
- Voltage unbalance was 7 – 8 %

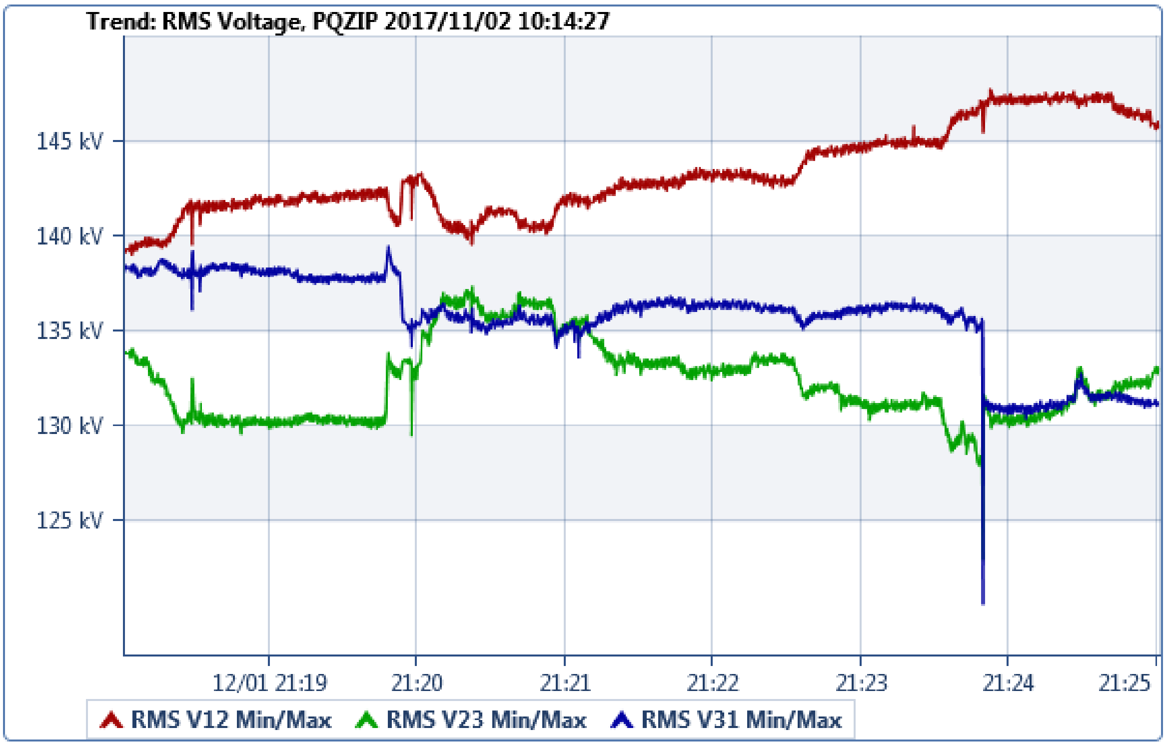

Figure 5-14: WEF over voltage event no.4: Three phase line to line voltage

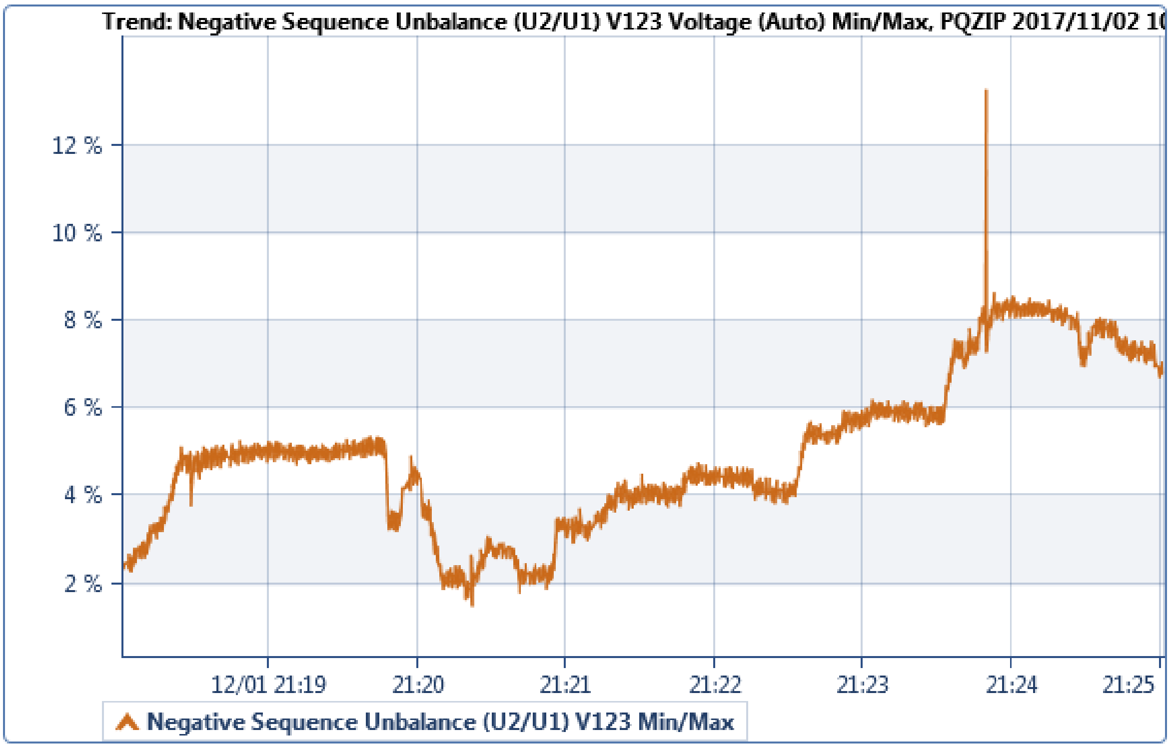

Figure 5-15: WEF over voltage event no.4: Voltage unbalance

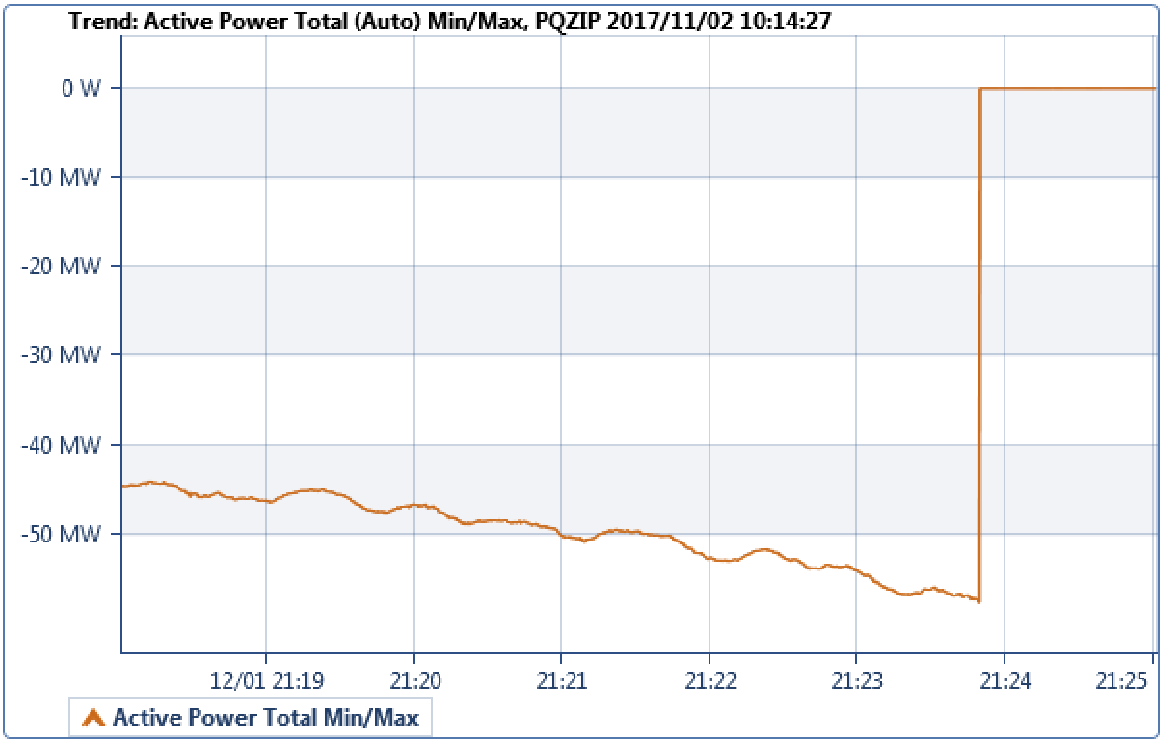

Figure 5-16: WEF over voltage event no.4: Total active power

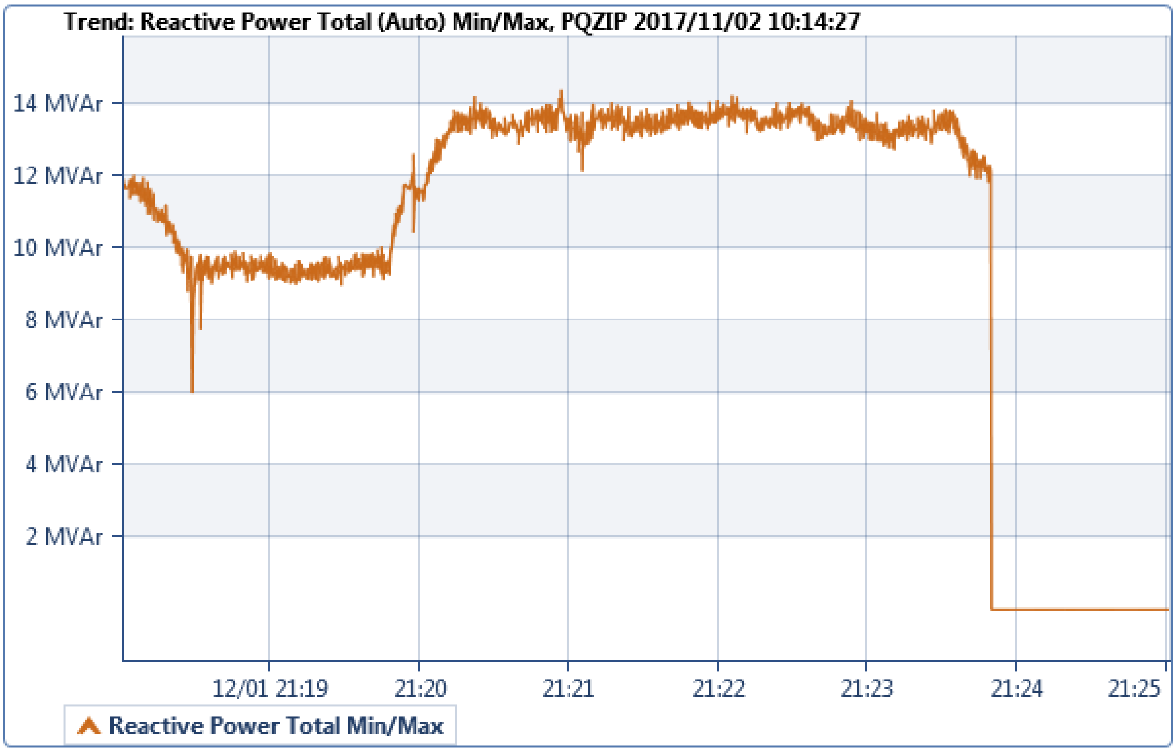

Figure 5-17: WEF over voltage event no.4: Total reactive power

During this event, not enough reactive power was absorbed to counter act the voltage rise caused by the active power injection of 56 MW.

5.2.6.3 Voltage ride through criteria

For both the high and low voltage trip listed above, the WEF was compliant with the grid code requirements for voltage ride through. High and low voltage events are plotted in terms of the grid code requirements for LVRT and HVRT as seen in Figure 5-18. During both events, the plant was allowed to disconnect as the events exceeded the requirements for voltage ride through.

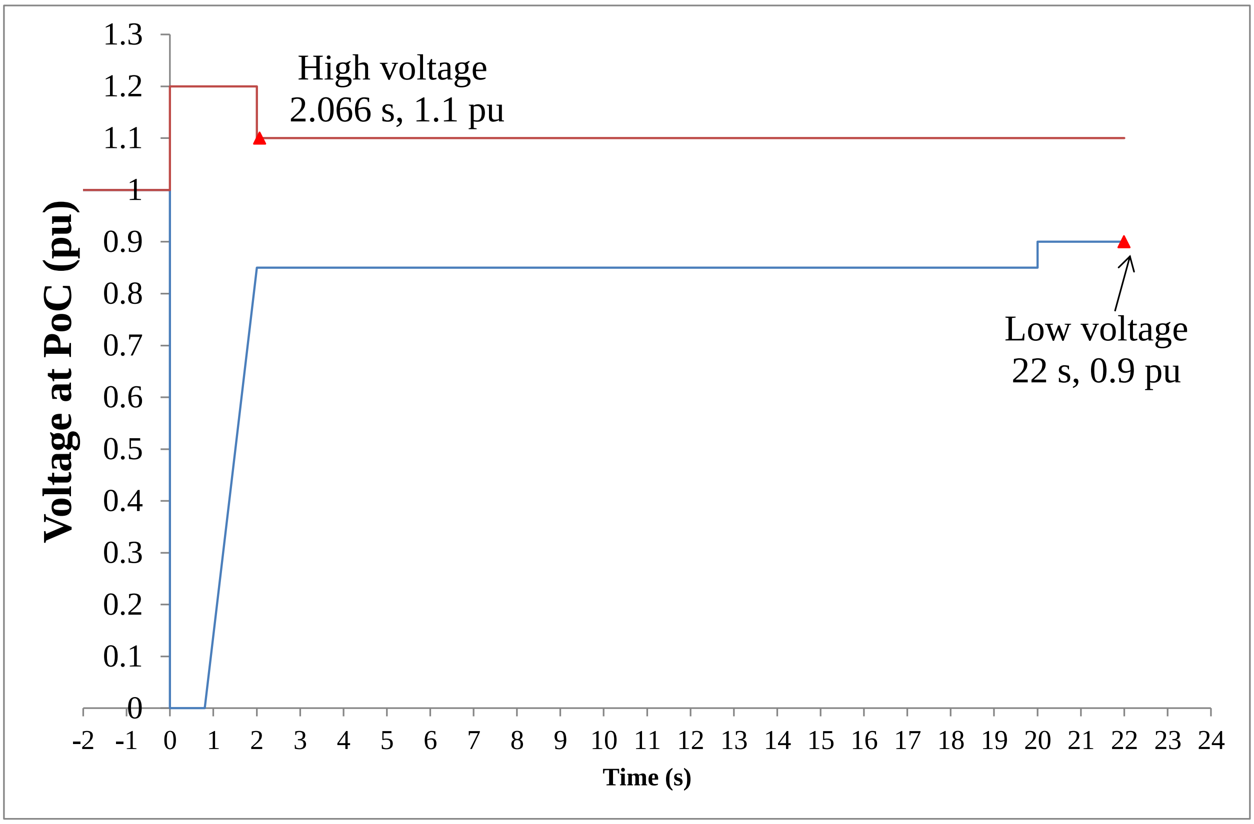

Figure 5-18: Voltage ride through requirements

5.2.7 Summary

During the critical network contingency, both RE facilities are unable to continue operating in voltage control mode. The resulting reduction in fault level increases the effect of active and reactive power on the voltage profile.

Switching to constant Q mode had limit success. Constant Q control relies entirely on manual intervention from the DSO control room. The mode cannot adapt to changing conditions such as load variations (especially passing of trains) and changes in active power output from the renewable generation (changes in irradiance and wind speed). If insufficient reactive power is absorbed, the plant may trip on over voltage. The opposite is also true that if too much reactive power is absorbed during low generation output periods, the plant may trip as a result of an under voltage condition. Both of these conditions were shown in the sections above. Determining the appropriate Q mode set point is almost impossible because of the severity of the voltage unbalance.

5.3 Voltage ride through measurements

At Jaguar substation, an ELSPEC Blackbox® was installed at the PoC of the PV facility in an attempt to recorder the RE facilities response to network faults when they do occur naturally. The logger was connected to the busbar VT's and feeder CT's. Recorded breaker operations from the SCADA system was used to reconstruct the system event.

5.3.1 Description of events

On 30 April 2015, there were subsequent faults on the 132 kV network between Giraffe and Jaguar. The breaker operations of the event are displayed in Table 5-4.

Table 5-4: Breaker trip indications

Date and Time	Indication	Description
30/04/2015 11:36:22.530	TRIPS	Jaguar Giraffe 1 132kV Bkr TRIPPED .
30/04/2015 11:36:25.230	IND	Jaguar Giraffe 1 132kV Bkr CLOSE - ARC
30/04/2015 11:36:25.630	TRIPS	Jaguar Giraffe 1 132kV Bkr TRIPPED .
30/04/2015 11:36:26.609	TRIPS	Giraffe DS Jaguar 132kV Bkr TRIPPED .
30/04/2015 11:36:29.000	ANLOG	Firefly Solar Jaguar 1 CT kV Analog UNDER VOLTAGE
30/04/2015 11:36:29.644	IND	Giraffe DS Jaguar 132kV Bkr CLOSE - ARC
30/04/2015 11:36:29.846	TRIPS	Giraffe DS Jaguar 132kV Bkr TRIPPED .
30/04/2015 11:39:22.556	IND	Giraffe DS Jaguar 132kV Bkr CLOSED - Tele Control
30/04/2015 11:39:53.432	IND	Jaguar Giraffe 1 132kV Bkr CLOSED - Tele Control

5.3.2 Recorded incidents

In Figure 5-19 the three phase voltages, active and reactive power from the PV facility is plotted during the network event. It is clear that at the time of the voltage dip, the active power of the plant decreases. Full active power output is only restored at about 5 min after the initial event.

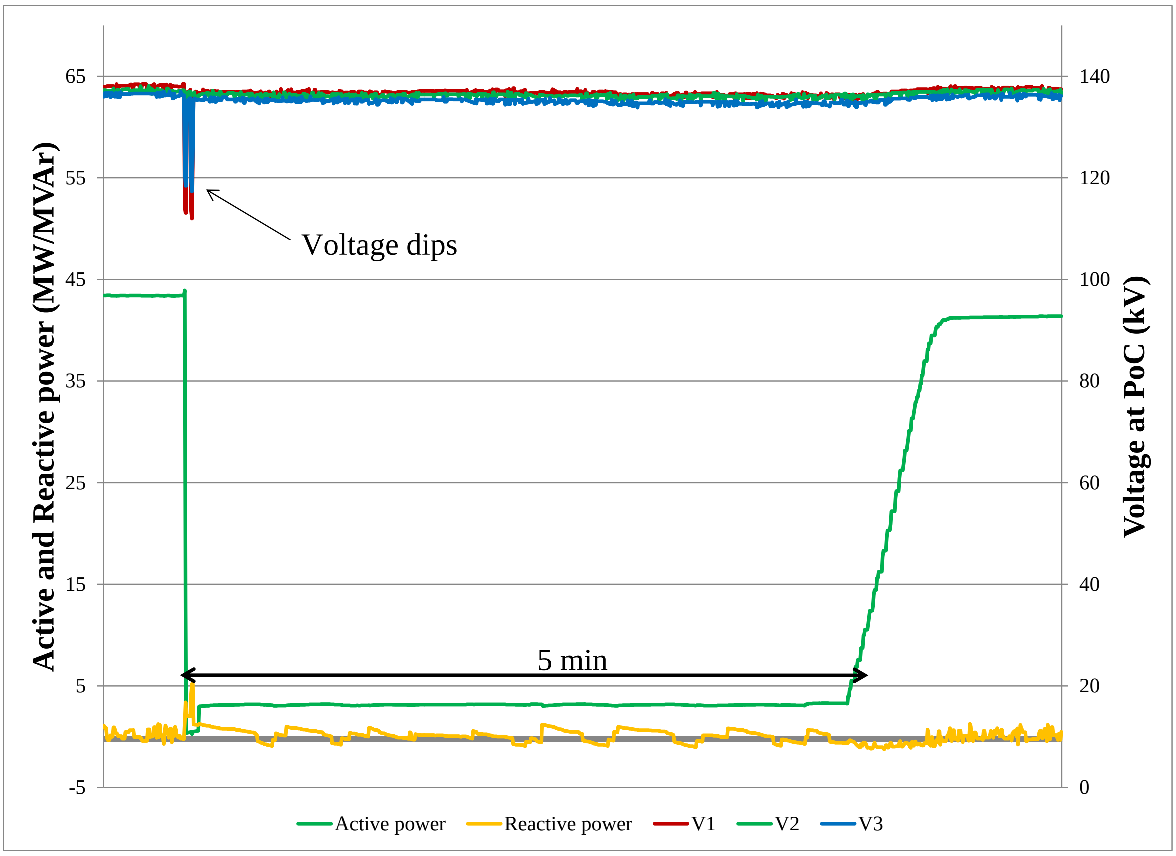

Figure 5-19: Overview of network events

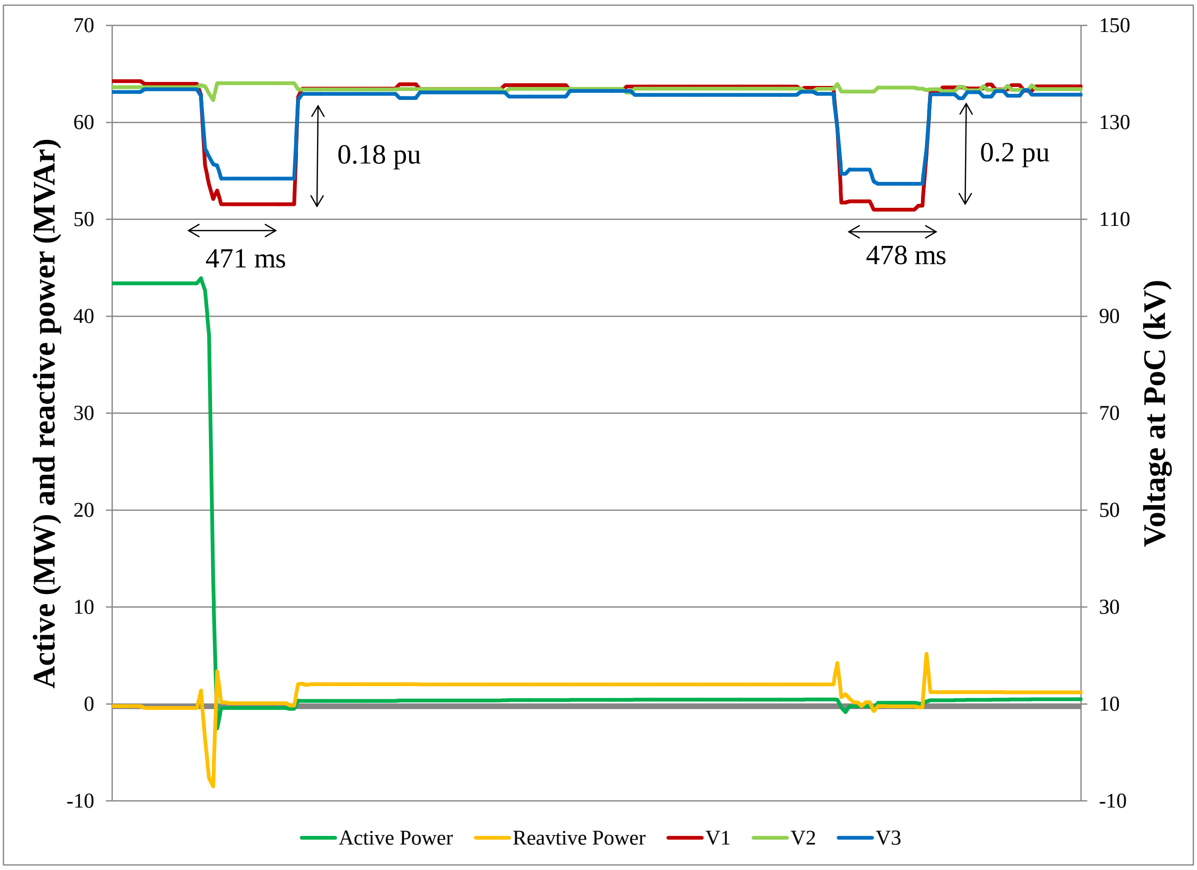

Figure 5-20: Voltage dip details

Details of the voltage dips are shown in Figure 5-20. Subsequent faults are 3 s apart – the dead time of the auto reclose cycle.

Both voltage dips displayed above was plotted within the LVRT grid code requirement in Figure 5-21. For both events, the plant should not a have disconnected from the grid, but stayed connected and provide reactive power support.

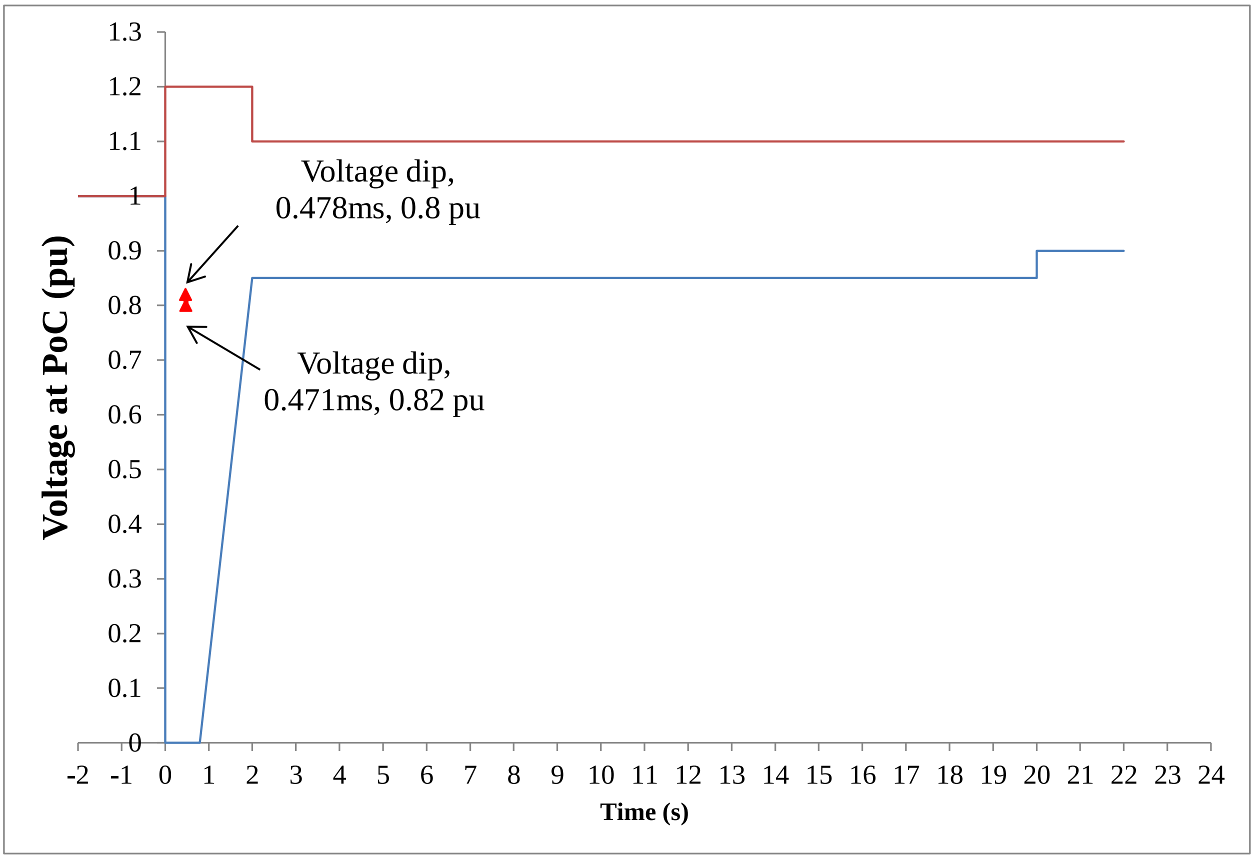

Figure 5-21: Voltage dip compliance

5.3.3 Summary

From the measurements, it is clear that the RE facility does not comply with the requirements of LVRT as stipulated in the grid code.

5.4 Supraharmonics measurements

5.4.1 Measurement setup

All measurement was done with an ELSPEC Blackbox® power quality logger. Measurements with the conventional CT's and VT's were taken. In an attempt to validate the measurements, a purely resistive voltage divider was also used.

The measurements are:

- 132 kV busbar at PoC
  - Current and voltage using conventional CT's and VT's
  - Voltage using a resistive voltage divider (only one phase)
- 22kV busbar (inside the PV facility – beyond the PoC)
  - Current and voltage using conventional CT's and VT's
  - Three phase voltage using a resistive voltage divider

5.4.2 Voltage divider setup

HV voltages are too high to measure directly with the Elspec recorder. In order to reduce the voltage to a measurable value, a purely resistive voltage divider was used as shown in Figure 5-22. Schematics, as well as the actual divider setup are shown.

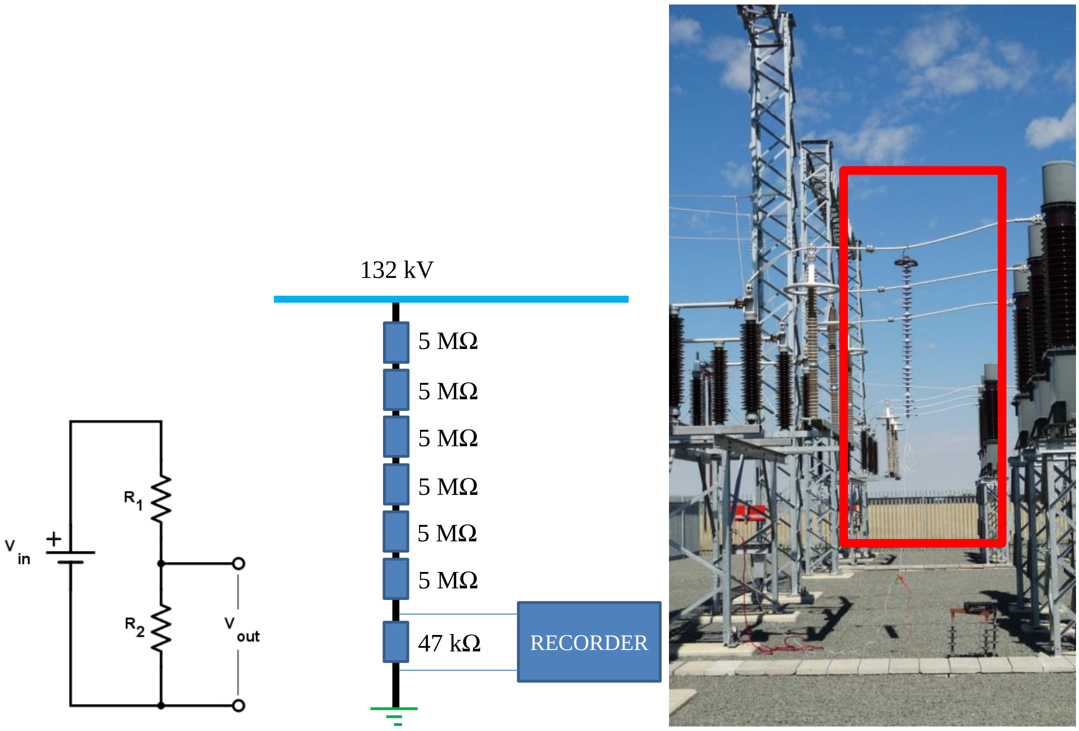

Figure 5-22: Voltage divider

Six 5 MΩ resistors in series with 1 x 47 kΩ resistor is used as the voltage divider. Measurements are taken with the recorder across the 47 kΩ resistor. The top part of the resistor divider is hooked onto the 132 kV line with an operator stick with the bottom part earthed.

Formula for a basic resistive voltage divider is given in equation (16)

$$V_{OUT} = \frac{V_{IN} \times R_2}{(R_1 + R_2)} \tag{16}$$

$$V_{OUT} = \frac{132000 \times 47000}{(30000000 + 47000)}$$

$$V_{OUT} = 206.48\,V$$

5.4.3 Measurements

Initial measurements were only taken with conventional CTs and VTs installed at the PoC. Measurements are shown for normal network conditions and when the network is reconfigured similar to the simulated network conditions.

A comparison between measurements taken with the conventional VTs and the resistive voltage divider is discussed later.

5.4.3.1 Normal network conditions

Figure 5-23 show a significate increase in voltage THD during PV generation. Distortion on the voltage waveform during generation is shown below in Figure 5-24

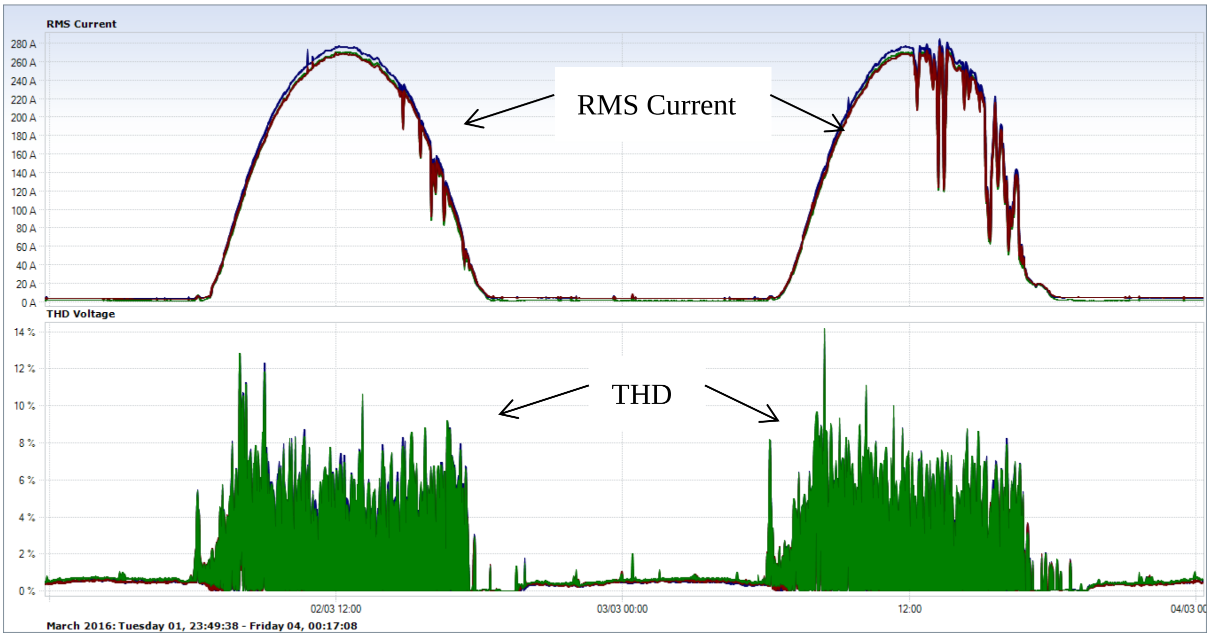

Figure 5-23: THD during PV generation

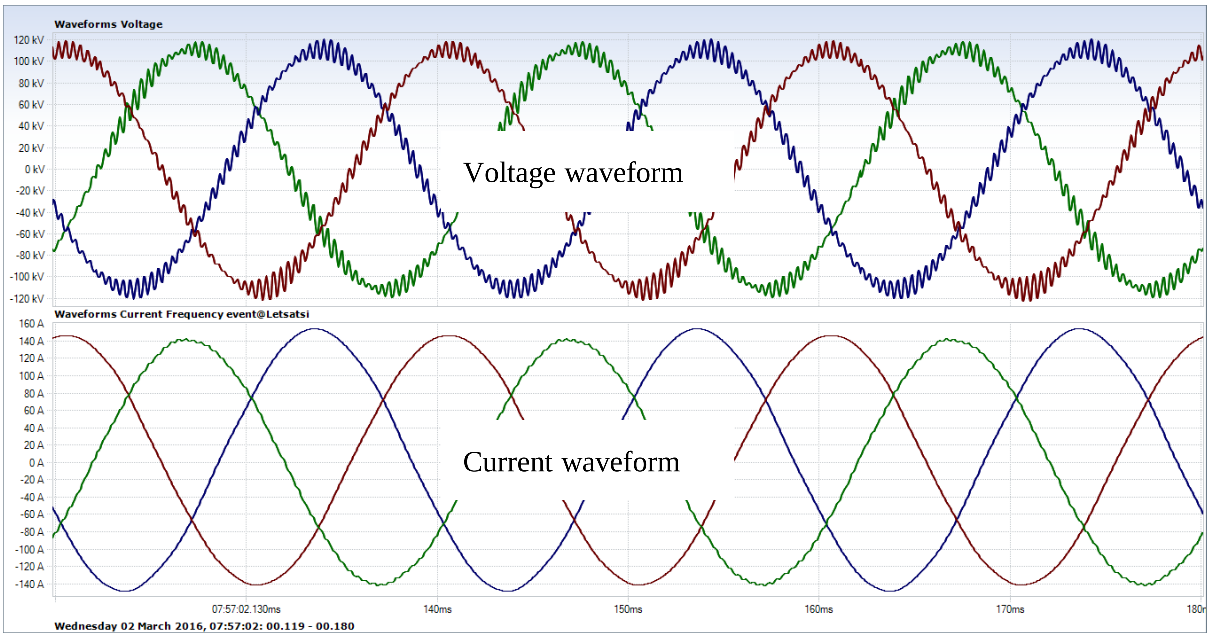

Figure 5-24: 132 kV voltage and current waveforms during generation

Under normal network conditions, a resonance point is calculated at 2689 Hz with impedance of 5351 Ω. The measured data indicate a peak at 2750 Hz or the 55th harmonic. Although the resonances are not exactly the same, it is within 61 Hz.

Waveform distortion is directly attributed to the PV generation. From the spectrum plot in Figure 5-25, there is an increase between 45th and 65th harmonics, peaking at the 55th harmonic.

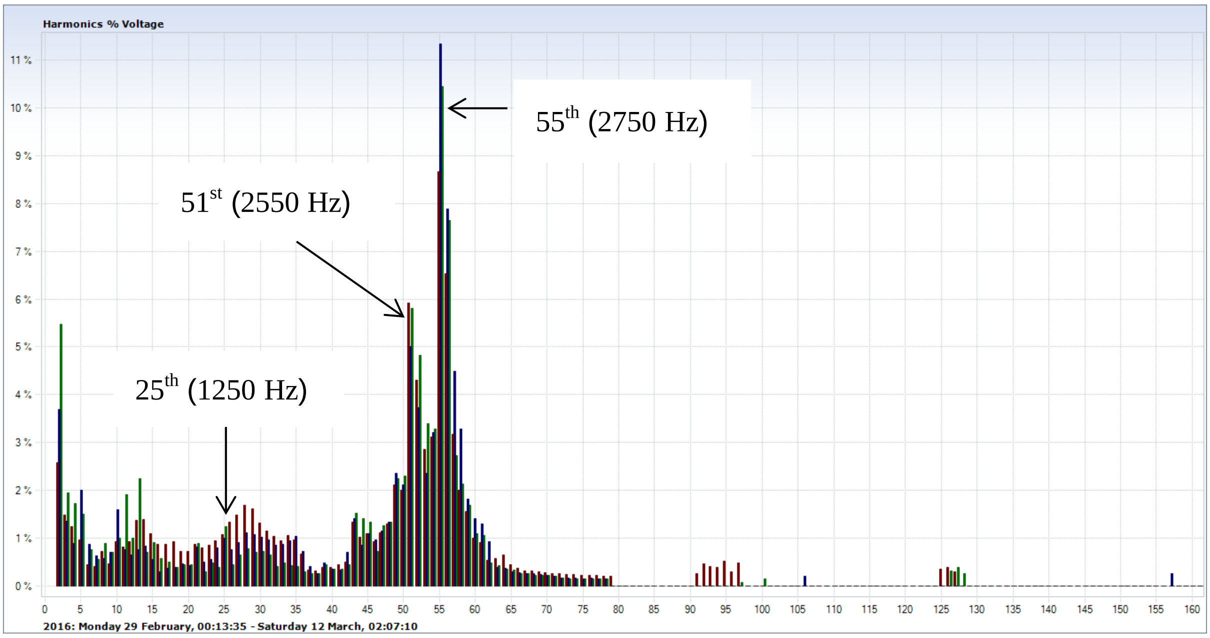

Figure 5-25: Harmonic spectrum analysis

Figure 5-26 shows the spectrum of harmonics above the NRS048 requirements of 25th (1250 Hz) harmonic.

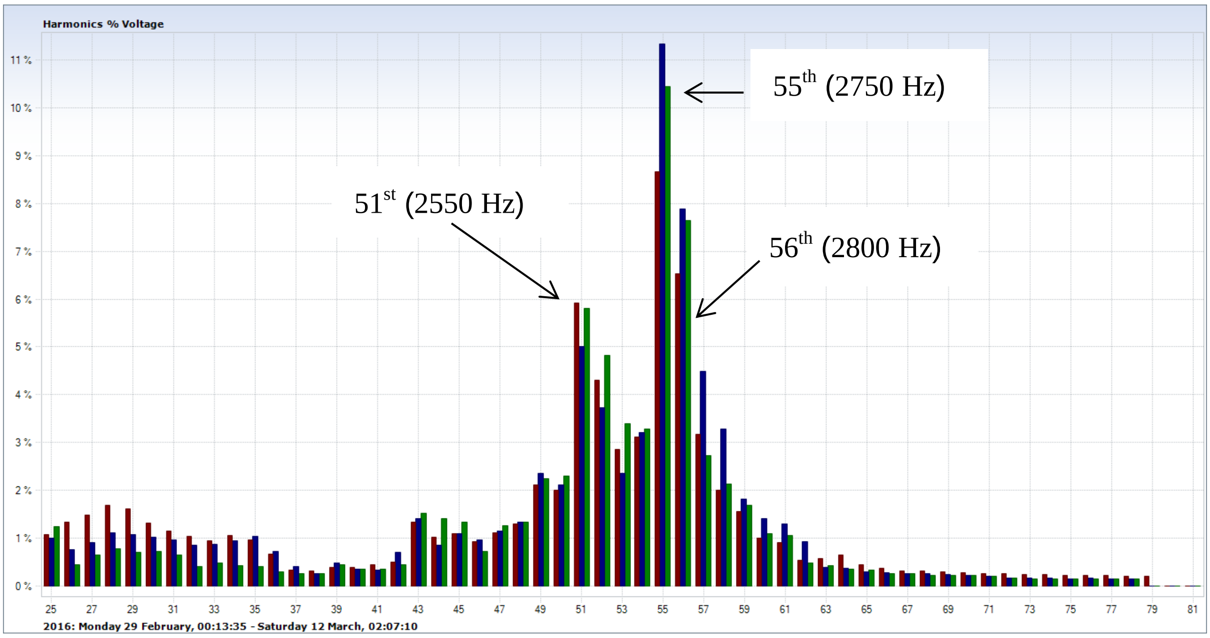

Figure 5-26: Supraharmonic range

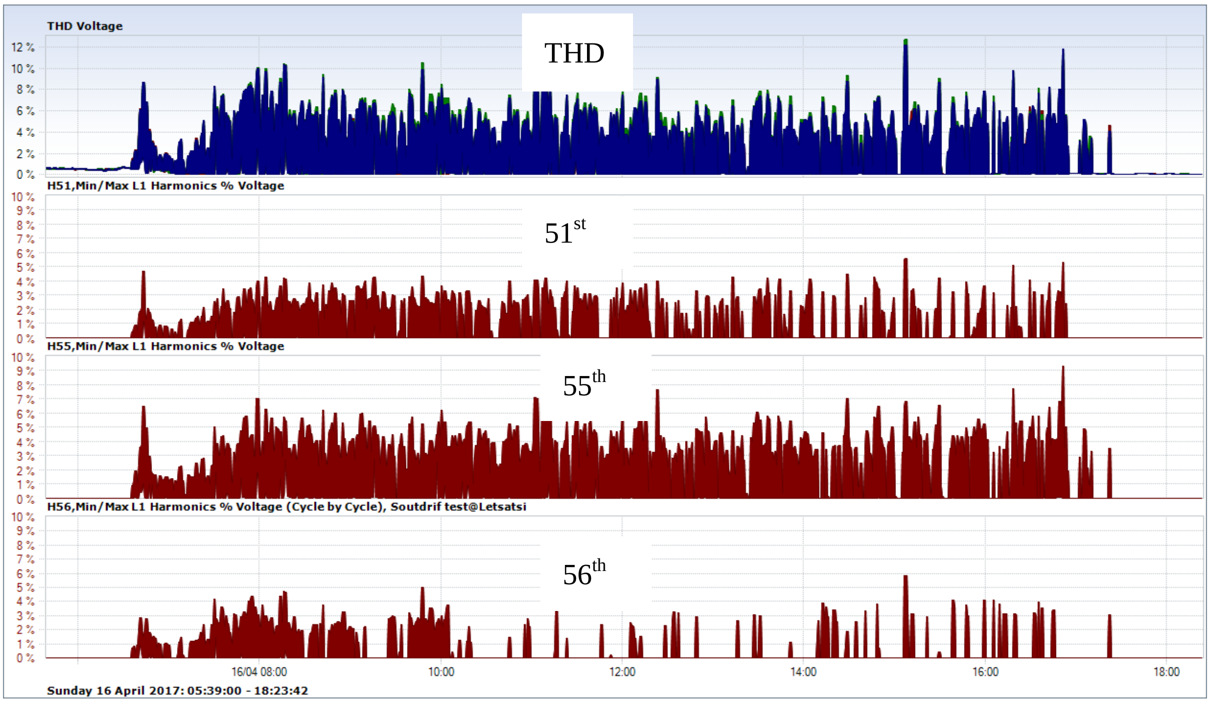

Figure 5-27: Intermittency of supraharmonics

Figure 5-27 plots the THD, 51st, 55th, and 56th harmonic (the most prevalent supraharmonics as shown in Figure 5-26) over a day period. Supraharmonics is not constant, but varies greatly over time, with some instances showing the supraharmonics dropping to zero.

5.4.3.2 Virginia Terminal network disconnected

Reconfiguring the network is done to determine if the network resonance points shift as indicated with the simulations. Virginia Terminal network is disconnected and the PV is only connected to the network from Harvard MTS. Table 5-5 shows the breaker operations during the network reconfiguration.

Table 5-5: Breaker operations

5/27/2017 11:22:02 AM	Vetrivier Houtenbeck 132kV Bkr OPEN
5/27/2017 12:01:36 PM	Vetrivier Houtenbeck 132kV Bkr CLOSE

Figure 5-28 and Figure 5-29 shows the RMS current of the PV facility and the accompanied voltage THD. There wasn't any notable reduction in voltage THD for the period the PV facility was disconnected from the Virginia Terminal network.

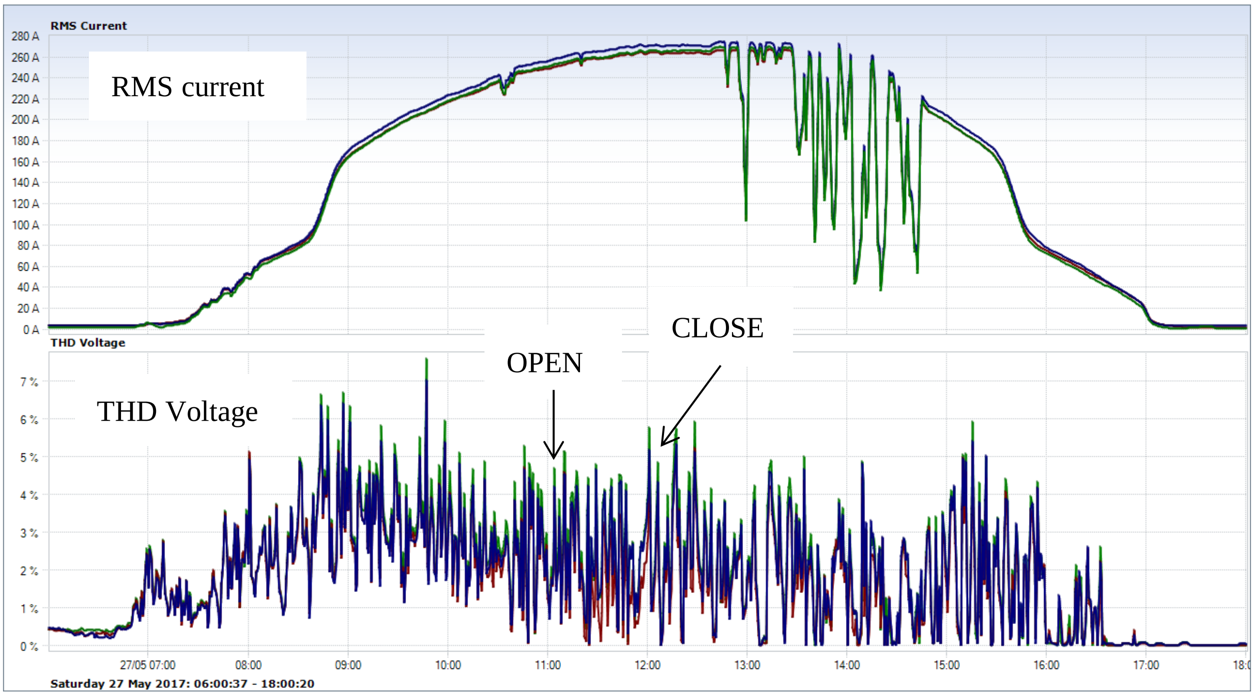

Figure 5-28: PV facility disconnected from Virginia Terminal network

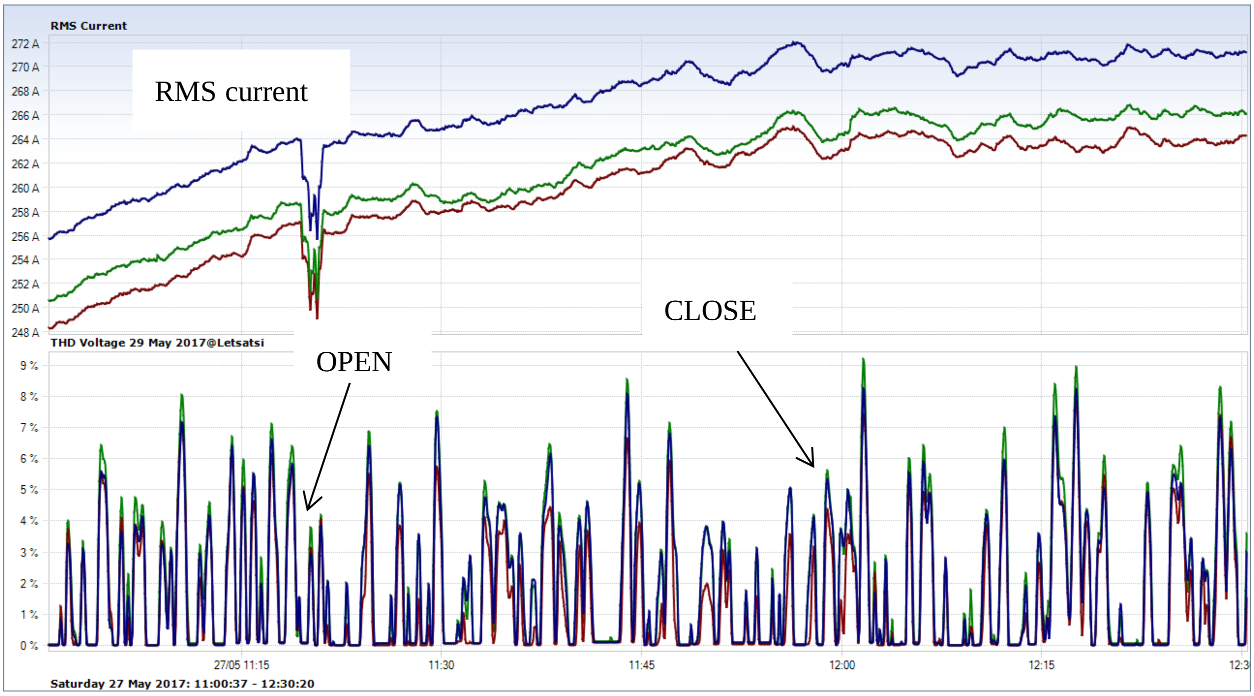

Figure 5-29: Detailed view of THD

With the Virginia Terminal network disconnected the impedance at 2689 Hz is calculated as 876 Ω. But there isn't a significate reduction of at the supraharmonic range.

5.4.3.1 Harvard network disconnected

Harvard was disconnected with the PV facility only being supplied from Virginia Terminal. Table 5-6 indicates the times when the 132 kV Harvard – Karee Traction breaker was opened and closed.

Table 5-6: Breaker operations

5/25/2017 6:49:33 AM	Harvard DS Karee Traction 132kV Bkr OPEN
5/25/2017 9:59:38 AM	Harvard DS Karee Traction 132kV Bkr CLOSE
5/25/2017 10:30:10 AM	Harvard DS Karee Traction 132kV Bkr OPEN
5/25/2017 10:54:53 AM	Harvard DS Karee Traction 132kV Bkr CLOSE

Figure 5-30 shows the voltage THD and current for the entire day. The breaker was opened early morning before any generation took place. When it was closed at 09:59, the voltage THD increased immediately. Opening again at 10:30, an immediate reduction is observed.

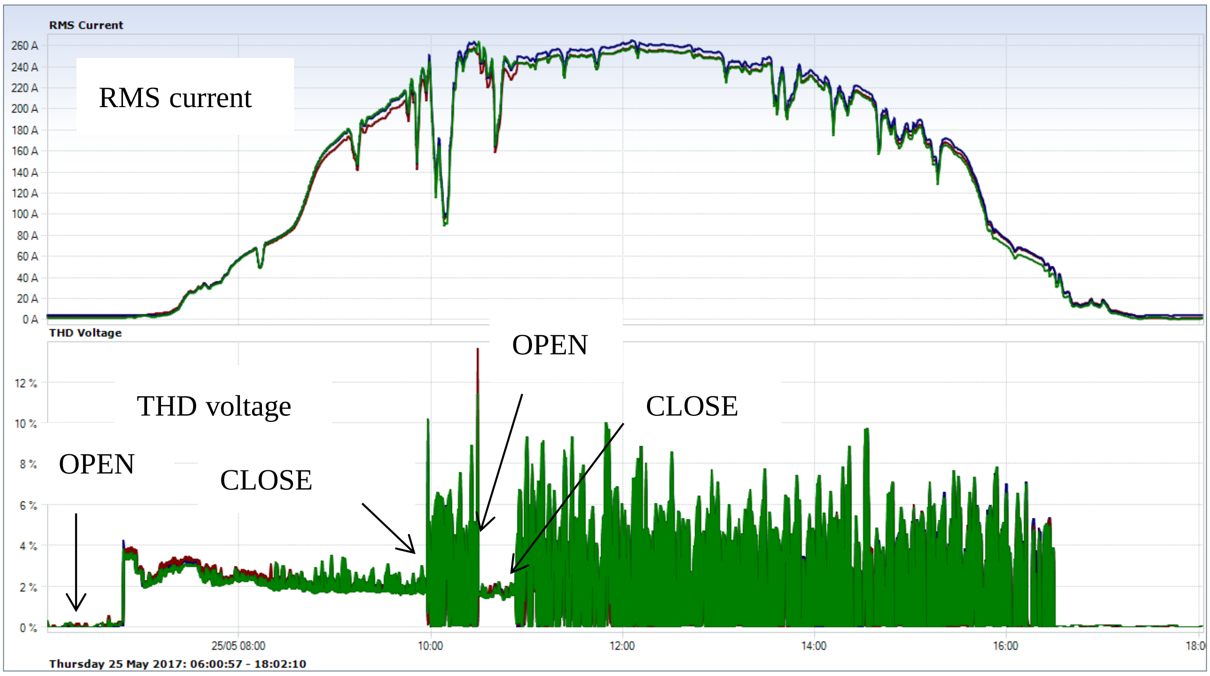

Figure 5-30: PV facility disconnected from Harvard

Figure 5-31 shows a more detailed view of the THD during the breaker operations.

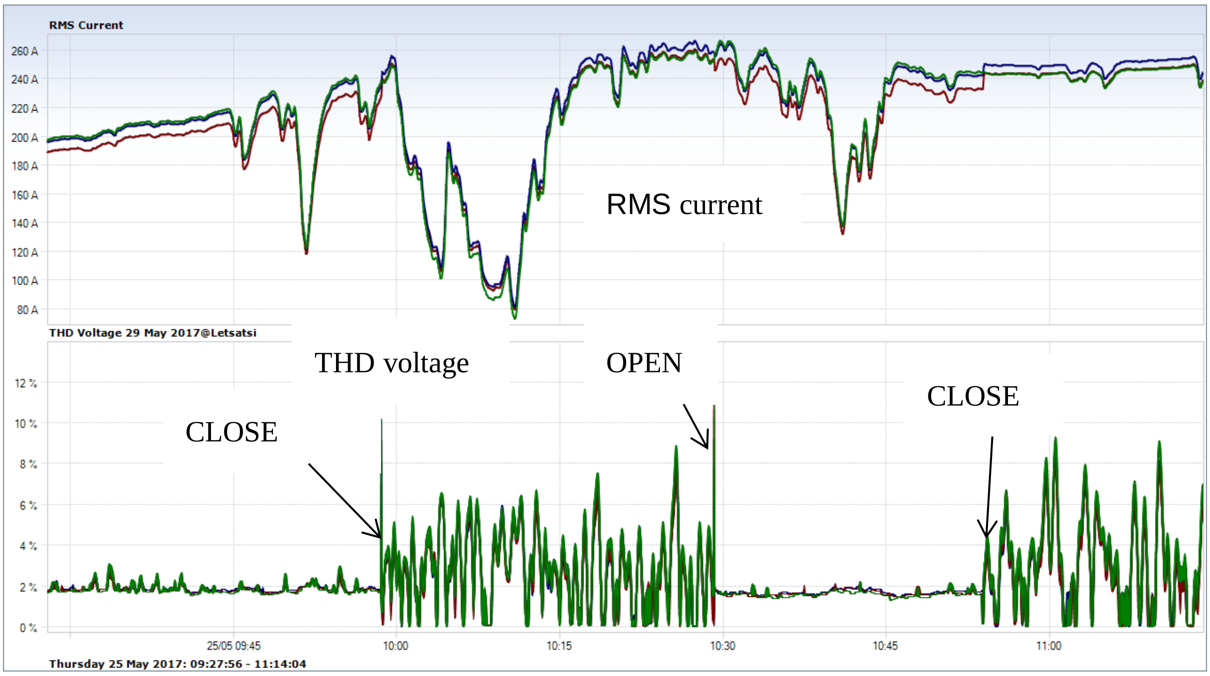

Figure 5-31: Detailed view of voltage THD during breaker operations

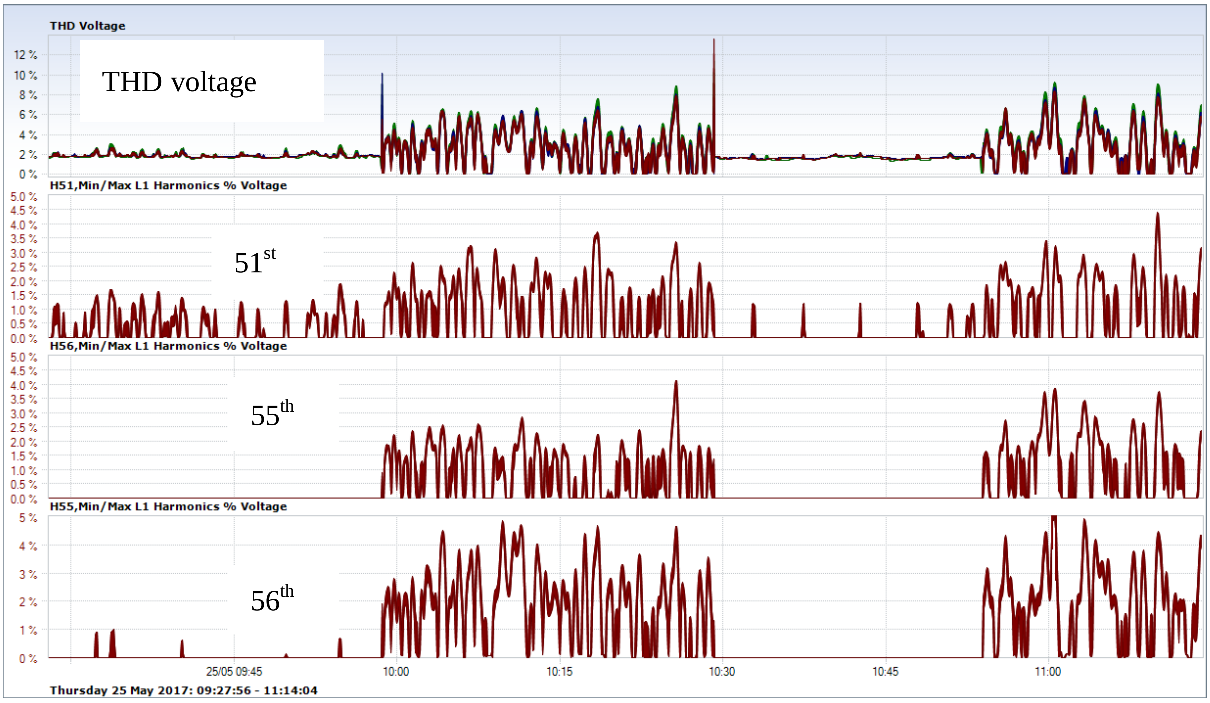

Figure 5-32: Individual supraharmonics during breaker operations

Figure 5-32 plots the THD voltage, 51st, 55th, and 56th during the breaker operation intervals. Again it shows the intermittency of supraharmonic generation.

The calculated impedance at 2689 Hz reduces to 105 Ω when the Harvard network is disconnected. This relates to a significant reduction in the supraharmonic range

5.4.3.2 Measurements with resistor divider

A 132 and 22 kV voltage divider was used as an alternative measurement source in an attempt to validate the measurements. In Figure 5-33, the voltage THD, as measured by the VT's and the voltage divider at the PoC are plotted over an hour. There is a distinct difference in amplitude of the two measurements, however the measurements do correlate in phase. Resonance in the 110 V measurement circuit is causing the increase in amplitude. Also note that only one phase was measured with the resistor divider due to a shortage of resistors.

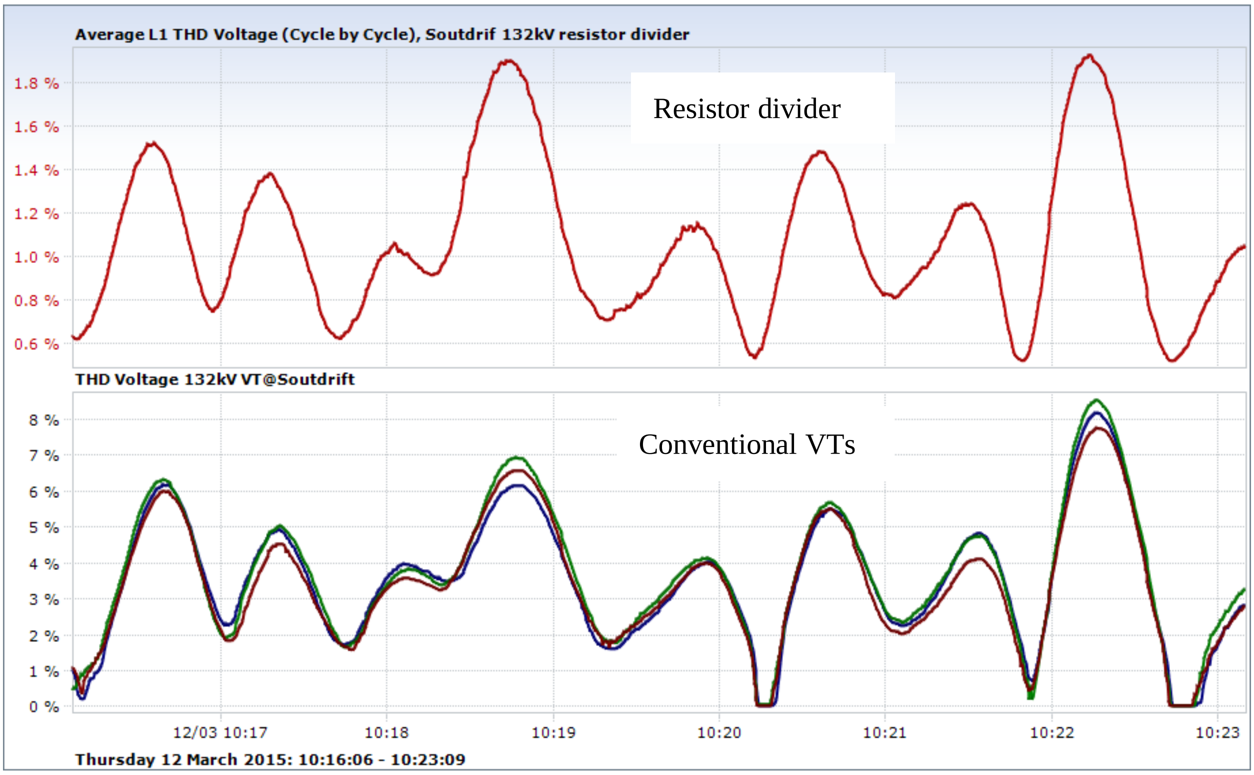

Figure 5-33: THD - Comparison of 132 kV measurement methods

In Figure 5-34, the 22 kV voltage inside the PV facility was measured with 22 kV VTs and a 22 kV resistor divider setup. These measurements are beyond the PoC inside the PV facility and have no bearing on grid code compliance as compliance is only assessed at the PoC. Measurements of the 22 kV voltage THD correlate with regards to phase and amplitude unlike the 132 kV measurements in Figure 5-33.

Also shown in Figure 5-34 is the 132 kV THD plot compared to the 22 kV THD plot. The 132 kV and 22 kV plots are not in phase, indicating different resonating impedances.

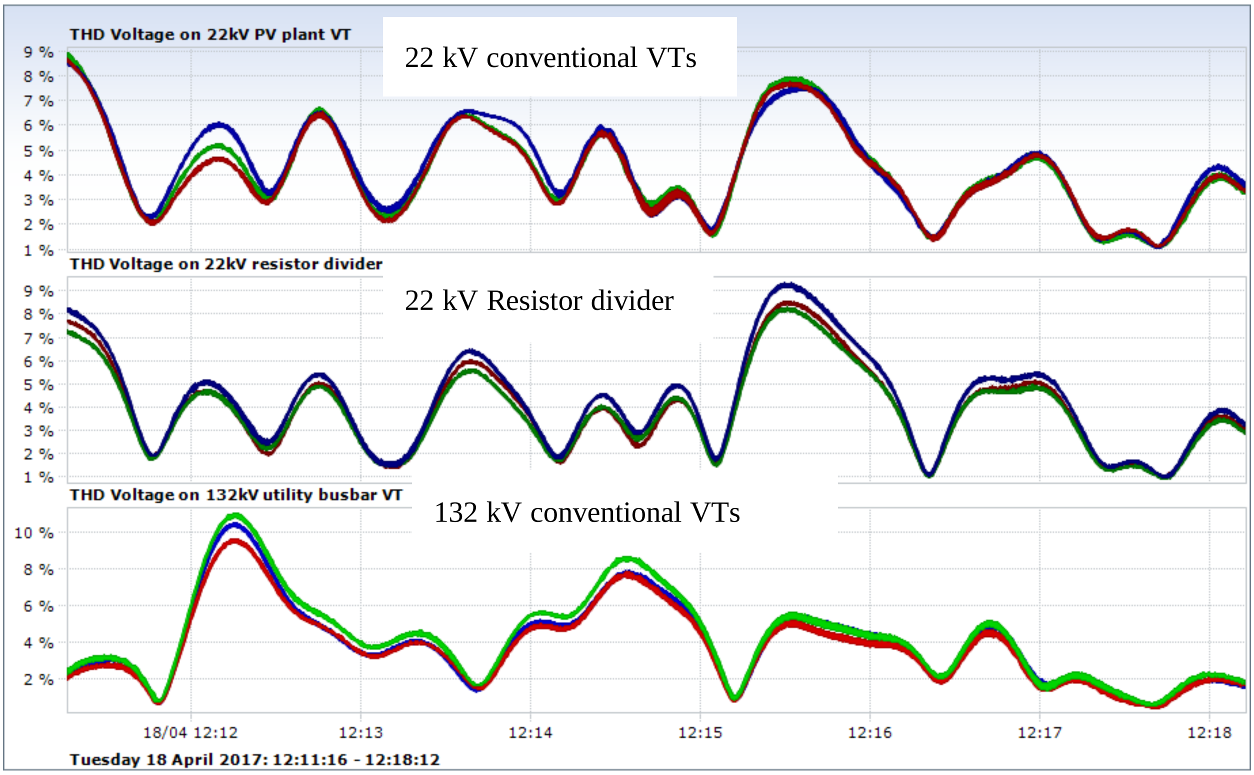

Figure 5-34: THD - Comparison of 22 kV measurement methods

5.4.1 Derating of transformers due to harmonics

Using the measured 22kV current harmonics (shown in Figure 5-35) and equations (9) to (13) as stated in IEC60076-16 [33], the derating factor of a typical MV/LV transformer is calculated. The first derating calculation, the current THD is calculated using all the harmonic order up to the 40^{th} harmonic as required by NRS048-2 [32]. All harmonic orders available are used to calculate the current THD in the second derating calculation.

Table 5-7: Derating factor calculations

	Transformer derating factor for current THD calculated up to 40^{th} harmonic order	Transformer derating factor for current THD calculated up to 256^{th} harmonic order
Derating factor	0.046 %	9 %

This indicates that higher order harmonics (which is not measured or assessed) has the biggest contribution to the derating factor.

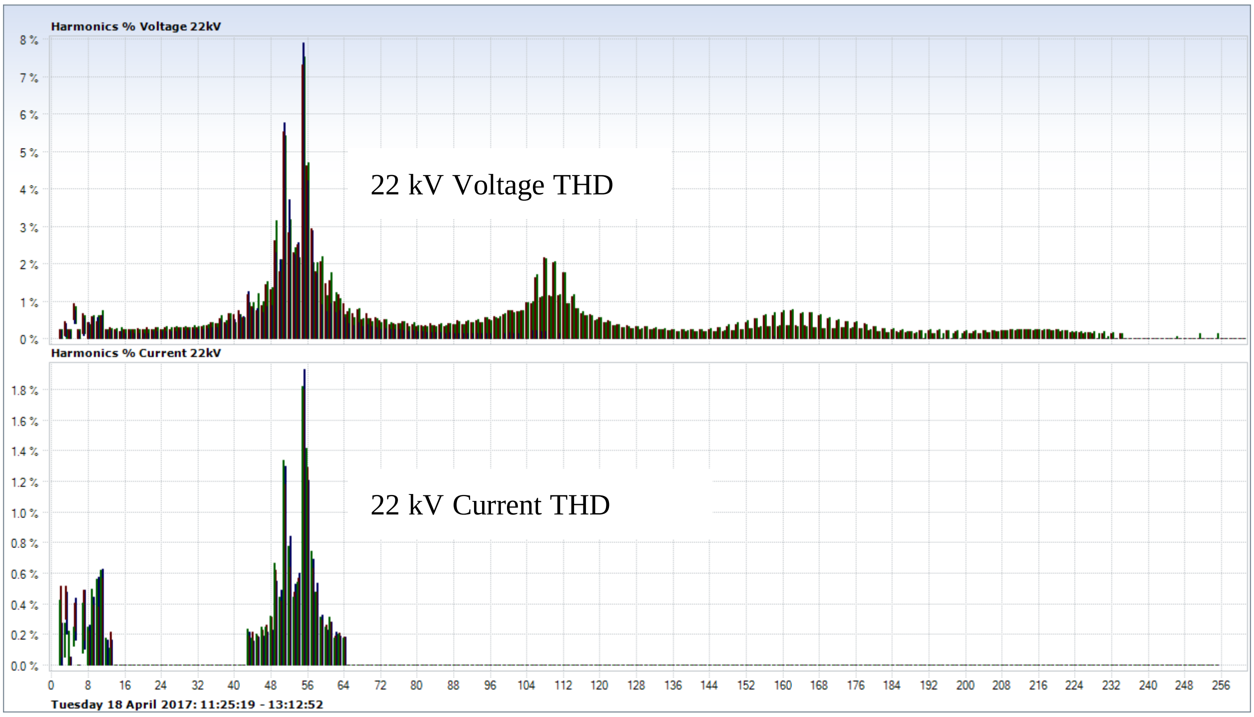

Figure 5-35: Voltage and current THD measured at 22 kV busbar

5.4.2 Summary

Measuring at the PoC (on 132 kV) with conventional VT's produces much higher values of supraharmonics than measuring with a resistor divider. The 22 kV measurements with both conventional VT's and the resistor divider produced equivalent results. Irrespective of measurement method, a clear correlation is shown between solar generation and supraharmonics present in the network. Supraharmonic generation is also altered by changing the network impedance with reconfiguring the network.

Comparing the 22 kV and 132 kV supraharmonic measurements (with the resistor dividers, Figure 5-33 and Figure 5-34), the supraharmonics decrease substantially from 22 kV to 132 kV. Thus at present there isn't a substantial risk to the NSP. The equipment of the PV facility is at risk with high levels of supraharmonics present in the 22 kV network. MV/LV transformers inside the PV facility will be de-rated with 9% to avoid over stressing the transformers.

Simulating a new 132 kV sub-transmission line from Harvard to Soutdrift, the calculated impedance at 2689 Hz is reduced to 909 Ω. The impedance is similar to when the Virginia Terminal network is switched out (876 Ω). When Virginia Terminal was switch out, there wasn't any significate reduction in supraharmonic emission. Similarly this option will not result in a significate reduction in the supraharmonic range. This is confirmed by [34], stating that a reduction in source impedance at 50 Hz will have limited impact on supraharmonics.

5.5 Reactive power support measurements

From the historic measured data, the critical outage for this specific network was assessed to validate the simulations done.

5.5.1 Measurement sources

Data from Eskom's SCADA system and metering database is used for this analysis. Power flowing into a busbar is displayed at negative and power flowing out of a busbar is displayed as positive as shown in Figure 5-36.

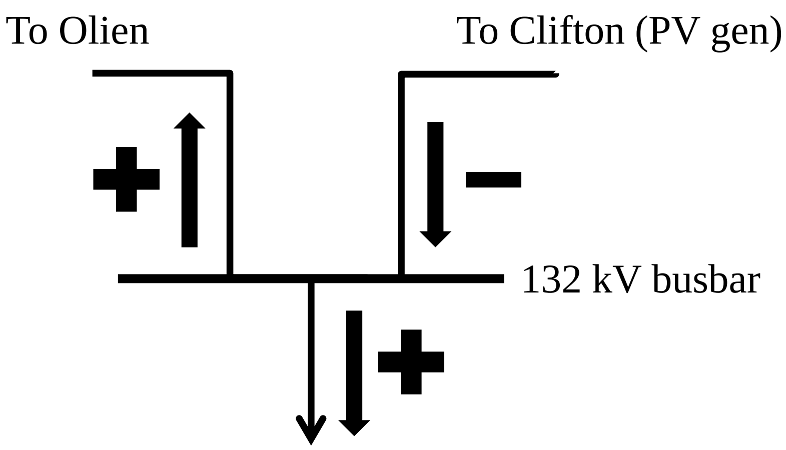

Figure 5-36: Active power flow direction

5.5.2 Description of events

Between 17 and 18 October 2016, 132 kV Olien – Karats line was taken out daily for maintenance. The line was returned during night time, when no work was being done. As shown in the simulations, this is the critical network scenario where the biggest reduction in fault level and the worst voltage regulation is expected.

5.5.3 Recorded incidents

Figure 5-37 shows the active (blue) and reactive (red) power output of the PV facility and the consumption of Karats mine during the critical network contingency. On the first day there is a perfect generation curve from the PV facility. Reactive power (red) is absorbed by the facility to counter act the voltage rise associated with active power generation. The plant is operating in voltage control mode and controls the voltage by controlling the reactive power.

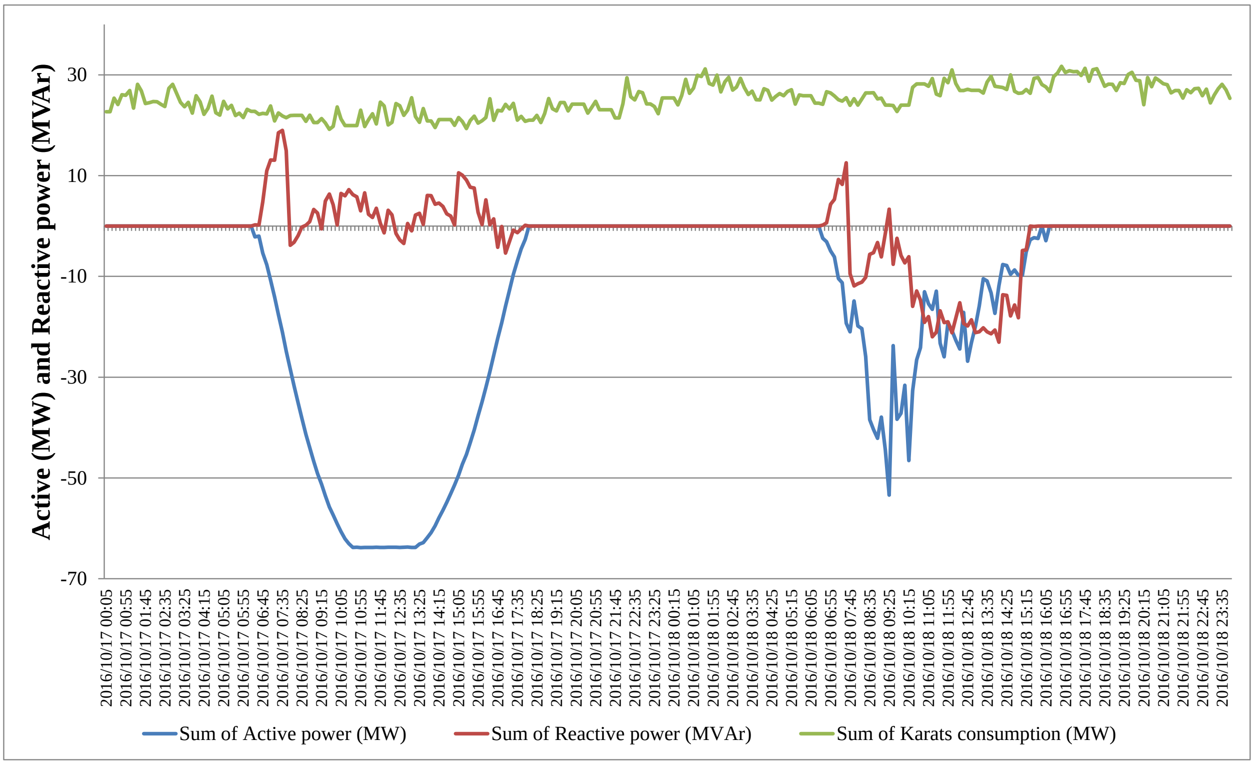

Figure 5-37: Active and reactive power output of PV facility

On the second day, the conditions are far less than perfect and the active power output of the plant varies significantly. The PV facility injects reactive power into the grid to support the grid voltage as seen in Figure 5-38. The PV facility provides maximum reactive power support by injecting 21 MVAr into the grid.

It is important to note that the active power consumed by the mine at Karats does not decrease during the critical network contingency even during the second day of the outage when the active power output of the RE generation was very low.

Figure 5-38 shows the 132 kV voltage profile (green) and ±7.5 % upper (red) and lower (blue) limits. During the first day of the outage (with optimal generation output from the PV facility), the voltage is unaffected. On the second day, with varying output from the PV facility, the voltage does decease as expected (even with full reactive power support), but it still maintained above the lower 7.5% limit.

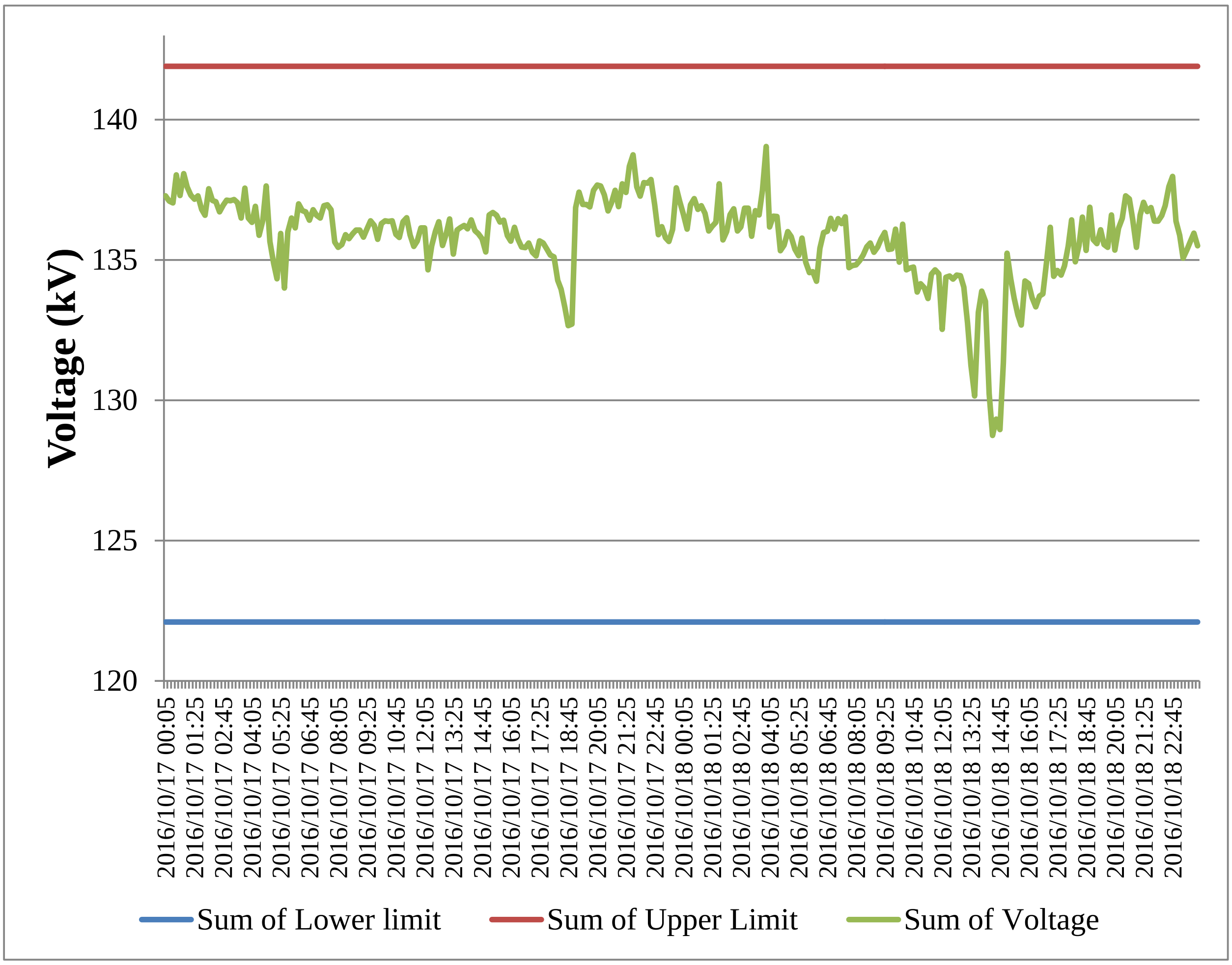

Figure 5-38: 132 kV voltage profile at Karats

At the lowest voltage measurement point (128.75 kV) the active power output of the plant was 7.84 MW (12.25 % of maximum power) and the reactive power exported to the grid was 13.75 MVAr (65.1 % of maximum reactive power). The plant did not export maximum reactive power (21.12 MVAr) at this time, since it followed the reactive power requirements in the grid code (section 2.2.6), when the active power was less than 20 % of maximum export capacity.

5.5.4 Summary

Measurements validate the claims made in the simulation studies that it is possible to use the reactive power capability of RE generators to maintain the grid voltage during critical network contingencies. This resulted in uninterrupted operations at the mine.

CHAPTER 6: CONCLUSION AND RECOMMENDATIONS

6.1 Renewable energy generation operations under unbalanced voltage conditions

Voltage unbalance on the network is caused by the single phase AC traction loads. It was present on the network before the RE facilities connected to the grid. Severity of the voltage unbalance was under estimated since the unbalance only becomes extremely high when the network is in its weakened state.

Simulations did not show the severity of the voltage unbalance under weak grid conditions. This is due to:

- Intermitted traction loading
- 30 min averaged loading data used in the simulation
- Errors in line transposition modelling contributing to voltage unbalance.

Simulations did highlight the potential effects of single phase AC traction load on voltage unbalance and to detrimental effect on connected RE generators under weak grid conditions.

STATCOM and SVC are proven technologies to lower the voltage unbalance on a network, but it will require capital investment from the NSP.

From the literature review, there are schemes available to reduce the voltage unbalance by using the reactive power capability of RE generators, but this too has its drawbacks. As seen in [30] some schemes only require software upgrades to the control algorithms of the turbines, but in an attempt to decrease the grid voltage unbalance, it creates double order harmonic oscillations on the turbine shaft which affects turbine performance.

6.1.1 Recommendations

For existing RE generators, switching the RE generator to Q mode, provides some relieve, but is by no means adequate. Since the long term effect of voltage unbalance on wind turbines could lead to increased maintenance costs and turbine failures [38] the recommendation is that RE generators be disconnected during this critical contingency and the time the grid is unavailable be counted towards the allowed grid unavailability.

Potential RE developers expecting to connect on sub-transmission networks with traction loads should be made aware of the voltage unbalance on the network during normal and weak grid conditions during the application phase.

If the grid conditions are unacceptable, potential RE developers might shy away from connecting to networks with very high levels of voltage unbalance and very low SCR. However, if the reactive power compensation of the RE generators can be effectively used to compensate for the grid unbalance, RE generators could be connected to networks previously deemed unsuitable for RE generation, thus unlocking further potential grid connections.

Further research is needed to determine if this will be a suitable mitigation strategy for voltage unbalance. Manufactures, regulators and grid operators needs to reach consensus on the future possibilities for voltage unbalance compensation using the reactive power capability of the turbines or inverters.

6.2 Voltage ride through

Some simulations used for grid code compliance do not reflect the facility’s actual performance during measured voltage dips. As stated in section 4.2, the models are provided by the developer of the PV facility. LVRT and HRVT capability is only evaluated by means of simulations, which does not always reflect the actual performance of the PV facility.

Intentionally creating an actual 132 kV fault on the network will affect other customers and isn't safe. Therefor it isn't practical to test a facility's compliance to LVRT and HVRT.

Type testing of units is performed by specialised service providers in EU, certifying the unit's compliance with regards to LVRT and HVRT. Certification is only applicable to individual units in terms of riding through a fault at the unit's LV terminals, not an entire facility's ability to mitigate a fault at HV level.

6.2.1 Recommendations

A dedicated event recorder needs to be installed at the PoC of each RE generation facility to continuously evaluate the facility's compliance to LVRT and HVRT. Added benefits would be to continuously monitor other aspects of grid code compliance as well.

With the data obtained from the recorders, models need to be adjusted to reflect the actual performance of the facility. Should a RE facility be found non-compliant, steps needs to be initiated by the NSP to ensure compliance to the codes.

6.3 Supraharmonics

Research into supraharmonics is still very new and will require extensive further research. The long term effect of supraharmonics on HV systems still needs to be determined. This study has given evidence of supraharmonics in HV network as a result of RE generation.

Network resonance points were validated with measurements at a PV facility, proving that simulations provide an adequate indication of network response.

Transformer losses calculations based on IEC 60076-16 indicates that excessive current harmonics in the supraharmonic range drastically increase the transformer losses, resulting in the possible de-rating of transformers.

6.3.1 Recommendations

The following recommendations are made:

- Models of RE generating units needs to be updated to reflect supraharmonic emissions.
- Limits for supraharmonic emissions needs to be formulated.
- A standardized method for measuring supraharmonics needs to be developed.
- A recorder capable of recording supraharmonics needs to be installed at the PoC for all RE generation.
- Network resonance plots at the PoC of potential RE generators needs to be simulated before any generating plants are approved.

6.4 Reactive power support

Providing reactive power support is well understood in power networks. With the advancement of power electronics, providing reactive power support when the facility isn't exporting active power is now possible. Measurements correlate with simulations done based on actual values.

It is currently not a grid code requirement to prove reactive power support during zero active power generation periods and there is no financial incentive provided.

6.4.1 Recommendations

Provision of ancillary services should be evaluated on a case by case scenario. It is up to the NSP to determine where and when reactive power support is needed. It has been proven that using the reactive power compensation of the RE generation, network strengthening can be deferred, until it is absolutely needed. As inverter based generation does not contribute to fault level [11], it cannot increase the fault level under weak grid conditions, but it can provide limited voltage support.

The ability to provide reactive power support at zero active power output should be a grid code requirement. It is still the decision of the NSP to utilize the functionality or not.

A commercial remuneration model needs to be developed for RE generators that are assisting with voltage support.

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