

# Dynamic modelling of an industrial micro-grid

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# Declaration

I, Rudolf Johan Erasmus hereby declare that the dissertation entitled “Dynamic modelling of an industrial microgrid” is my own original work and has not already been submitted to any other university or institution for examination.

A handwritten signature in black ink, appearing to read 'R.J. Erasmus', with a long, flowing horizontal stroke extending to the right.

R.J. Erasmus

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Signed on the 20th day of November 2018 at Potchefstroom.

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## Abstract

With a decentralized approach to power system development gaining traction in both developed and under-developed countries, the realization of the next generation of power distribution network is identified as the Smart Grid. A Smart Grid utilizes all the current advances made in power electronics, renewable generation, and communication to provide a resilient, environmentally friendly network without the large scale infrastructure needed in centralized generation networks.

A key part to the realization of the Smart Grid is the microgrid, which is a combination of various distributed energy resources and loads connected to the same point of common coupling. The microgrid can be situated in an industrial facility, commercial park or residential area and provides the owner with a resilient energy source, reliable power quality, economically beneficial operating options and an environmentally friendly footprint. Microgrid design and implementation vary vastly and hence a lot of possible research and development opportunities are available.

To better understand and improve dynamic response within a microgrid, which is one of the areas of development, a site-specific representative model can be created. The analysis and improvement of dynamic response within a power system ensure proper operation throughout its service lifetime, optimizes maintenance focus and minimizes production loss due to unnecessary power dips and outages.

A concise modelling approach, documented in this dissertation, provides the necessary background, design, verification and validation processes to create such a model. This is done by combining research on different microgrid standards, compositions, power quality events and control methods, with operational field data obtained from the site being modelled.

Results obtained emphasized the improvement on islanded network voltage and frequency stability, through improved generator and energy storage control. Operational limits and improvements to system operation philosophy were identified and

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tested. Overall this representative model provides a platform to analyse microgrid performance, identify possible improvement opportunities and test future development plans without taking the financial risk of blindly deploying such practices on site, making it a valuable asset.

**Keywords:** *Microgrid, Dynamic model, Power quality, Smart Grid, Distributed energy resources*

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# List of Acronyms

**ATP** Alternative Transient Program

**AVR** Automatic Voltage Regulator

**BPA** Bonneville Power Administration

**DFIG** Double Fed Induction Generator

**PQ** Power Quality

**RER** Renewable Energy Resource

**SG** Smart Grid

**DER** Distributed Energy Resource

**DG** Distributed Generation

**EMTP** Electromagnetic Transients Program

**ESS** Energy Storage System

**PCC** Point of Common Coupling

**LV** Low Voltage

**DNO** Distribution Network Operator

**LC** Local Controller

**VSI** Voltage-Source Inverter

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**VSD** Variable Speed Drive

**MV** Medium Voltage

**EMS** Energy Management System

**PV** Photovoltaic

**MPP** Maximum Power Point

**MAS** Multi-Agent System

**MPC** Model Predictive Control

**MGCC** Microgrid Central Controller

**PSO** Particle Swarm Optimization

**ANN** Artificial Neural Network

**SLD** Single Line Diagram

**DPL** DIgSILENT Programming Language

**DSL** DIgSILENT Simulation Language

**MPQC** Microgrid Power Quality Conditioner

**IEEE** Institute of Electrical and Electronics Engineers

**IEC** International Electrotechnical Commission

**CENELEC** European Committee for Electrotechnical Standardization

**NEMA** National Electrical Manufacturers Association

**NRS** National Regulatory Standard

**THD** Total Harmonic Distortion

**EU** European Union

**UC** Unit Commitment

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**IGBT** Insulated Gate Bipolar Transistors

# List of Symbols & Subscripts

## List of Symbols

|        |                      |
|--------|----------------------|
| $V$    | Voltage              |
| $u$    | Electrical potensial |
| $I$    | Current              |
| $f$    | Frequency            |
| $S$    | Apparent Power       |
| $P$    | Active Power         |
| $Q$    | Reactive Power       |
| $Z$    | Impedance            |
| $X$    | Reactance            |
| $R$    | Resistance           |
| $\psi$ | Flux                 |

## List of Subscripts

|      |                          |
|------|--------------------------|
| $SC$ | Short Circuit            |
| $OC$ | Open Circuit             |
| $O$  | Output                   |
| $R$  | Red Phase/First Phase    |
| $W$  | White Phase/Second Phase |
| $B$  | Blue Phase/Third Phase   |

---

|     |                      |
|-----|----------------------|
| $d$ | Direct               |
| $q$ | Quadrature           |
| $L$ | Line to Line voltage |

# Chapter 1

## Introduction

### 1.1 Background

Within this chapter, modern power system problems faced by first and third world countries are discussed in a manner that will reveal various research opportunities and motivate the chosen research topic of dynamic model development to study transient events within an LV microgrid.

#### 1.1.1 Power system philosophy migration

Power system development typically uses two different design philosophies, which are the centralized and decentralized generation approach. Centralized generation focuses on large generating units that provide whole regions with energy through the use of transmission lines, where the energy typically only flows in one direction. Decentralized generation focuses on multiple units within the same region, typically connected to the distribution lines of the network, all providing and trading energy with one another and any loads present.

Currently, the widely used central generation philosophy of the past is losing traction

within the modern power system environment. Depending on the region, reasons for this migration to a decentralized generation is driven by various factors [8].

Technology advancement in both the power electronics and Distributed Generation (DG), in general, have made it possible and affordable for both residential and commercial sectors to employ their own small means of power generation. This provides an economic incentive.

With the worldwide push to use more renewable sources, such as the well-know Paris Agreement, a lot of pressure is placed on industries and countries to better utilize renewable sources of energy.

In underdeveloped countries, the need for reliable energy production and distribution to the masses is a priority. Studies tend to suggest investing in a nationwide generation, transmission and distribution infrastructure is not necessarily effective in cost or time. Smaller generation sites such as micro- and nanogrids may be a better solution [9].

Through this worldwide demand, the migration to a decentralized power system is motivated.

### **1.1.2 Smart Grid realization**

The Smart Grid is the term mostly used to describe this intelligent, decentralized electricity distribution grid of the future. Although the concept of this Smart Grid is sound and it seems to be the solution to various problems faced by an ever-developing energy dependent civilization, certain implementation problems exist that need to be solved.

These implementation problems vary from the lack of inertia in mostly inverter-based generation sectors to the communication and control strategies needed to effectively manage the significant amount of Distributed Energy Resource (DER) units present within this system [9].

For managing a spectrum of different smaller sources with the eye on providing re-

newable and stable energy to a certain campus or area, a system structure known as a microgrid can be utilized. This microgrid can be implemented in a residential area, commercial park or manufacturing industry, grid-tied or not.

A microgrid is a relatively old concept but has only recently been identified as a viable tool due to the large technology advances made in both power inverters and renewable energy production [10]. Each microgrid developed in the future will most certainly differ in components, size, implementation environment and/or specific operating objectives. The need to understand deviations in dynamic behaviour and developing representative models preceding microgrid construction is thus needed to efficiently construct the power system of the future.

## **1.2 Problem statement**

As with the Smart Grid, well-planned implementation of a microgrid is crucial and both steady state operating strategies and transient behaviour control/management should be well documented to ensure the best results. Following standard engineering practice, a representative model should be developed to support any design development. Although various sources within the available literature do utilize different types of models to validate any results and conclusions, how these models are created and their level of correlation with an implemented system is not well documented. The research topic "Dynamic modelling of an industrial microgrid" provides an opportunity to develop and document the needed knowledge, while providing a validated modelling approach that will be useful in future microgrid development.

This model should focus on producing viable/accurate dynamic results of microgrid transient operation. Lack of detailed system information and its negative effect on simulation results (in component modelling and control) should be compensated by using synchronous field data representing the industrial microgrid's current state of operation. Applying field data in such a manner allows industries to develop functioning models that can be used in their development towards self sufficient energy

production.

## 1.3 Research Objectives

Research objectives are to identify the necessary standards, control strategies, important power system dynamic behaviour and a suitable simulation environment for the model. This will be done by identifying and consulting peer-reviewed literature that is currently seen as the authoritative source for standards, composition and operation of microgrids.

Develop a reproducible model development approach and model. By developing a representative dynamic model utilizing the available literature and data, critical system operations and exchanges can be observed. A dynamic model also provides an opportunity to further study the effect of transient events from the various microgrid components on both stability and Power Quality (PQ).

Verification and validation of the model to ensure simulation results can be used to analyse and improve the industrial microgrid. Verification is done using available literature on the dynamic response of microgrids and well-documented case studies. This combined with validating the model with field data will not only reinforce the viability of the chosen model development approach but may provide results necessary to better understand and improve further microgrid development within a similar environment.

## 1.4 Overview

Chapter 2 provides a literature study on microgrid composition and control, microgrid standards and general power quality terminology all from peer reviewed literature.

Chapter 3 contains a trade-off study for simulation environment selection and docu-

ments model development and verification.

Chapter 4 documents model validation through the use of field data.

Chapter 5 identifies operational areas within the test facility that can be improved and documents simulation results of improvements.

Chapter 6 concludes the dissertation and provides future work topics.

# Chapter 2

## Literature Study

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*Basic knowledge necessary for understanding microgrid composition, operation and standards are discussed in section 2.2. Section 2.3 discusses dynamic response, modelling and power quality aspects that should be taken into account, which is necessary for understanding model development in chapter 3. Finally, section 2.4 concludes the chapter.*

---

### 2.1 Introduction

Research done does not only focus on specific dynamic issues faced in a microgrid but to understand the fundamentals of microgrids, their possible composition and operation.

Section 2.2 addresses this need, starting by discussing the definition of and reasons for incorporating a microgrid [1, 3, 11–13], making the benefit and practicality of implementation clear. The most popular components found in microgrids and how they are incorporated successfully are discussed [1, 2, 14–16], including the typical control processes followed to ensure proper and efficient operation [3, 10, 13, 17]. Finally, knowl-

edge on how microgrids are going to take shape in the near future is discussed by listing the various standards being developed specifically for their use and implementation as a smart microgrid forming part of the smart distribution grid.

Section 2.3 establishes the area specific focus of the dissertation: How dynamic occurrences such as different stability phenomena [1,12,16,18] and PQ events [12,19,20], that may cause operational constraints, should be taken into account and solved with the eventual goal of implementing this knowledge into a representative microgrid model.

The main academic sources guiding research direction and validating research motivation are identified as [1,3,13,19–24].

## **2.2 Microgrid fundamentals**

Throughout literature the agreed upon definition for a microgrid is the combination of various DERs, which constitute units such as a generator, Renewable Energy Resource (RER) and Energy Storage System (ESS), as well as static (time invariant) and dynamic (time variant) loads that are connected to the same Point of Common Coupling (PCC) [3] such as in figure 2.1.

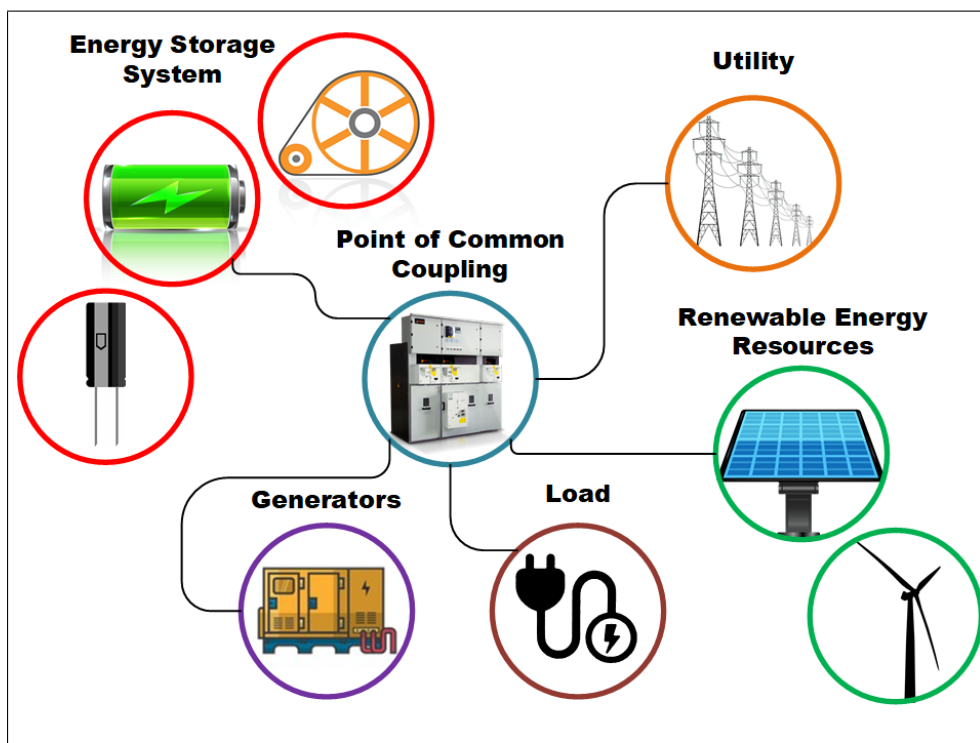


Figure 2.1: Typical microgrid composition

Specific sizing limits to define the range wherein a system may be called a microgrid is still debated and regulations discussing this should be finalized in the near future.

The sudden popularity of microgrids around the world is not without merit as table 2.1 lists various ancillary services provided by microgrids [11].

Table 2.1: Microgrid ancillary services

| Ancillary services               | Description                                                                                                                                                                                                                                                                                                                                                               |
|----------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Regulation and load flow         | By monitoring load flow and utility energy tariffs and limitations and then planning and adjusting DER generation a microgrid can avoid and improve economic and physical limitations when importing power.                                                                                                                                                               |
| Supply reserves                  | As the DERs incorporated have faster responses when frequency deviates, the microgrid can provide a frequency response spinning reserve. If an agreement is reached with the system operator they can provide backup energy reserves for any other critical loads on the network (with the management of critical and non-critical loads provided by the system manager). |
| Provide power quality correction | DERs can be utilized for voltage regulation and power factor correction through the supply or absorption of reactive power which negates the need for capacitor banks and other means of traditional voltage regulation.                                                                                                                                                  |
| Islanded operation               | The microgrid's islanded operation mode makes operation independent from the utility's grid possible. This mode can be entered from a black start or transitioned to from grid-connected mode.                                                                                                                                                                            |

A privately controlled microgrid can provide its owner with the ability to control various operational factors within their local network.

### 2.2.1 Microgrid composition - Distributed Energy Resources

As discussed a microgrid can be comprised out of a variety of DERs each with its own benefits. Being comprised out of a variety of local sources has the following benefits [1]:

- Utilizing smaller DERs opposed to the traditional centralized power system approach provides the system with much-needed flexibility and promotes comprehensive and efficient energy use. This approach to energy production, storage

and consumption allows local control, mitigating the challenge to supply energy from large centralized thermal power stations over long transmission lines to remote distribution networks where the end users connect. A typical large power plant has a generation efficiency of 35-55% before distribution losses and 30-47% after. Depending on how well a system incorporating DERs is designed, efficiency can reach above 80% without any transmission losses [1].

- Provides much-needed network security and stability. Deploying DERs as part of a microgrid on the user end of the grid significantly increases the continuity of reliable power supply to any critical loads, helping the microgrid owner to contain operational risk as the contributing factors are under local control in case of any disaster that may cause a grid collapse.
- Has a smaller area and lower initial capital investment than a comparable transmission and distribution network while granting the ability to meet special demands. Being close to its load, transmission losses are removed and waste energy can be contained with proper layout/design. This makes it an attractive solution for remote locations where a grid connection is not simple.
- Using renewable energy as an electricity source locally diversifies the traditional energy mix, being more environmentally friendly than traditional fossil fuel sources. As global warming concerns increase the pressure and necessity to better utilize any environmentally friendly energy generation is also increasing.
- The mix of ESS and DG addresses the different problems of the individual DERs. Local ESS mitigates the inherent variability of RERs (resulting from irradiation or wind velocity).
- RER use controllable power electronics to connect to the grid, improving the generation of active and reactive power generation.

Designing and analysis of a microgrid require an in-depth understanding of the various DERs and how they are used. The most common of these DERs used, as identified

in the literature, and how they support the overall objectives of a microgrid are discussed further in this section.

### Rotating generation

Knowledge of the operation and principles of synchronous generators (diesel or petrol combustion engines) is assumed and will not be analyzed.

**Doubly fed induction generators** - A Double Fed Induction Generator (DFIG) is a generator that is connected to the electrical network on both the rotor and stator sides (rotor typically connected through power electronics) as depicted in figure 2.2. This configuration is more difficult to control than a standard asynchronous or synchronous generator but with the correct implementation offers various benefits. These benefits include separate control, overactive and reactive power output, higher output power efficiency than normal induction motors, diminishing inverter rating and the ability to operate in both subsynchronous and oversynchronous operating areas [14,25].

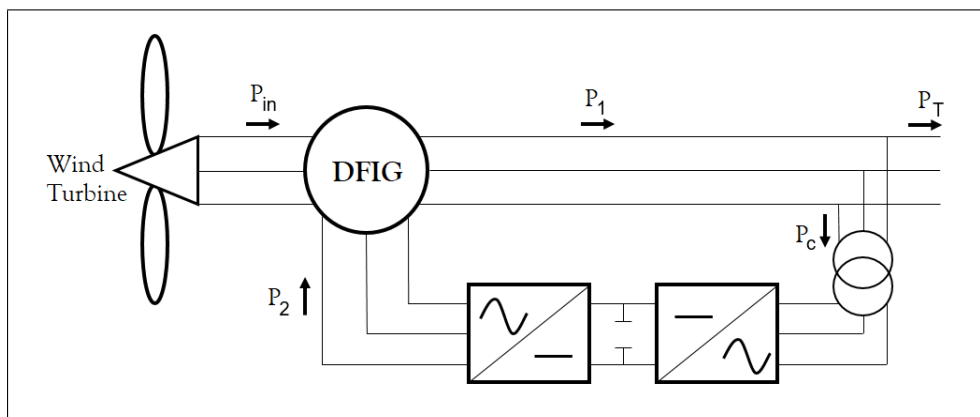


Figure 2.2: Double Fed Induction Generator connection to variable speed wind turbine. Adapted from [1].

Due to their ability to produce stable power when connected to a variable mechanical energy source (speed, torque). These DFIGs are ideal for use with wind turbines, which can experience a sudden change in wind speed at any time. When operating in its

subsynchronous area of operation the rotor absorbs energy from the grid, whereas it injects energy onto the grid in its oversynchronous operating area. Note that the stator of the DFIG produces energy in both scenarios [14].

Utilizing the front-end converter's DC link voltage amplitude as seen in figure 2.2, the active power flow into the DC link can be controlled while the inverter on the rotor side is responsible to adjust desired torque amplitude, to be equal to the generated or consumed active power. Both inverters, when employing the right control strategy, can be used to adjust the power factor of the wind turbine allowing the generator to operate as a reactive power compensator or generator [14,25].

**Microturbines** - Microturbines are small in size and weight, have lower emissions when consuming fossil fuels, a higher durability and life span, reduced maintenance and produce less noise than for example a diesel generator which makes them very attractive solution for microgrids.

A microturbine typically consists out of three parts namely the compressor, combustor and turbine which in conjunction can burn fuel such as methane, natural gas, petrol or diesel to generate electricity through the use of a permanent magnet synchronous generator. Unit power for a microturbine can range from 25 kW to 300 kW [1].

Two typical configuration methods to connect a microturbine to the grid [1]:

1. Inverter connected - A single-shaft microturbine rotates at speeds between 50 000 and 120 000 rpm which produces a high-frequency AC. This current is firstly converted to DC and then back to grid frequency AC through the use of an inverter.
2. Directly connected - When using a split-shaft microturbine, the gas and power turbines can be connected through the use of a variable-speed gear which reduces speed enough for the generator to produce AC at a fixed frequency.

Figure 2.3 depicts two grid connection methods used for microturbines. For an in-depth discussion on the mechanical operation of a microturbine please refer to [1].

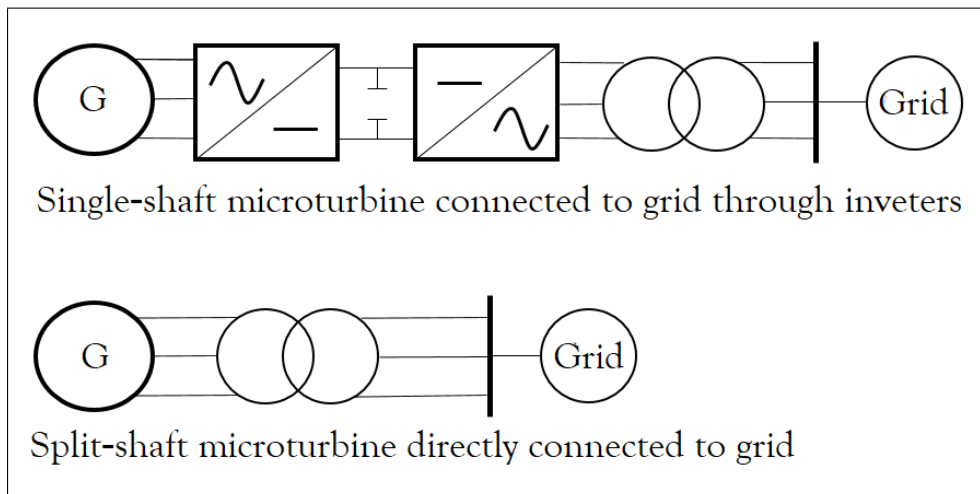


Figure 2.3: Microturbine connection methods. Adapted from [1].

## Renewables

**Photovoltaic electricity** - Photovoltaic (PV) electricity is obtained from solar cells that converts photons (solar irradiation) to electrons [2]. Different solar cells exist; namely crystalline silicon, amorphous silicon thin film, and compound thin film. Each of these cells has different efficiency and cost benefits and a proper project study should be done to identify the ideal cell for a project's specific demography and budget. A typical solar system (off-grid or grid-tied) constitutes the following [1]:

1. PV array - Consisting out of two or more solar cell modules that are formed by encapsulating solar cells.
2. DC combiner box - This combines the various DC circuits of the PV array into one high-current output. The DC combiner box adds the first level of protection (overcurrent, countercurrent and lightning) and can be further aggregated as the final input to the inverter.
3. Off-grid or grid-tied inverter - Both inverter types converts DC to AC. An off-grid inverter is typically a voltage-forming inverter and a grid-tied inverter is a current-source which disconnects from the network when the grid voltage is

removed, because it needs the grid voltage as a reference.

4. DC and AC distribution box - Contains DC or AC switchgear and metering equipment.
5. Battery storage - This is optional and discussed later in this section. Its main goal when cooperating with the PV system is to ensure power supply balance and continuity as the PV array's energy production is dependent on the sun's irradiance.
6. Controller - Does overall control and data collection of the system and may be integrated into the inverter.

PV arrays are one of the most used renewable sources within a microgrid. Understanding its dynamic behaviour is important for developing a useful equivalent model needed for dynamic modelling of the microgrid. A non-ideal PV cell's equivalent circuit can be modelled as a current source, with a series and shunt resistance completing the final components used in this model as seen in figure 2.4 [2].

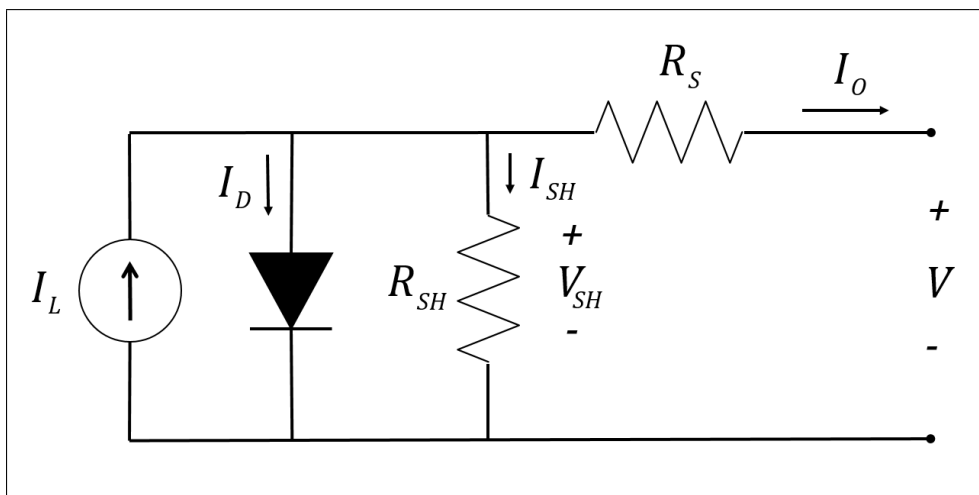


Figure 2.4: PV cell equivalent circuit. Adapted from [1].

The output current of the PV cell can be calculated as

$$i_O(t) = i_L(t) - i_D(t) - i_{SH}(t), \quad (2.1)$$

with output current  $i_O(t)$ , the PV cell generated current  $i_L(t)$ , the diode current  $i_D(t)$  and the shunt current  $i_{SH}(t)$  [2]. By Ohm's law, the output current relates to the shunt voltage,

$$v_{SH}(t) = v(t) + i_O(t)R_s, \quad (2.2)$$

with  $v_{SH}(t)$  as the voltage across the shunt resistance,  $v(t)$  the output voltage and  $R_s$  the series resistance. High quality PV cells (low series resistance and reverse saturation current with high shunt resistance). Allow short circuit current  $I_{SC}$  to be expressed as  $I_{SC} \approx I_L$  [2].

Inverters used with PV arrays will continuously search/track the Maximum Power Point (MPP) of the cells. This point is where the cells produce the maximum amount of electrical power for the received irradiation at that time. Figure 2.5 illustrates this point to be somewhere between short and open circuit. Equation (2.3) determines the MPP.

$$p_{PV}(t) = v_{PV}(t)i_{PV}(t) \quad (2.3)$$

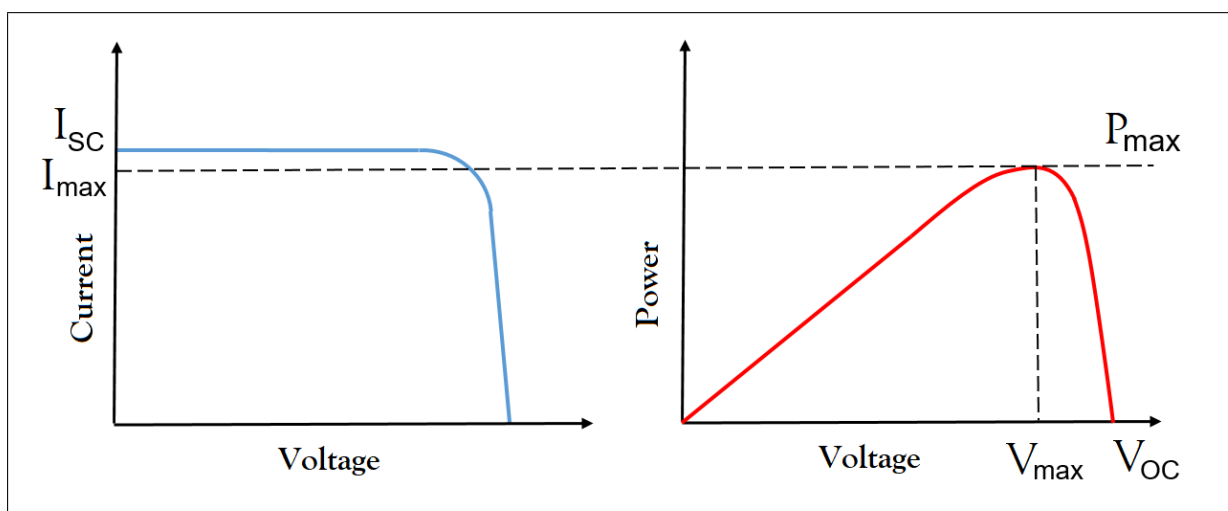


Figure 2.5: Determining the MPP on a PV cell. Adapted from [2].

**Wind turbines** - Wind energy is an attractive source of renewable energy that utilizes the kinetic energy stored in wind, converted to electrical energy by the use of a

generator.

Wind turbines have various configurations. As the focus of this chapter is specifically AC microgrids, only the connection methods and components needed for AC grid-tied turbines are listed below [1]:

1. Directly connected - An asynchronous generator can be used to connect the wind turbine directly to the grid which allows direct current injection.
2. Inverter connected - A synchronous generator is connected to an inverter which injects stable AC electricity on to the grid.
3. Hybrid mode connection - A doubly fed induction generator is used (section 2.2.1). The stator is directly connected to the grid with the wound type rotor connected to a grid-tied inverter.

These different connection configurations are depicted in figure 2.6.

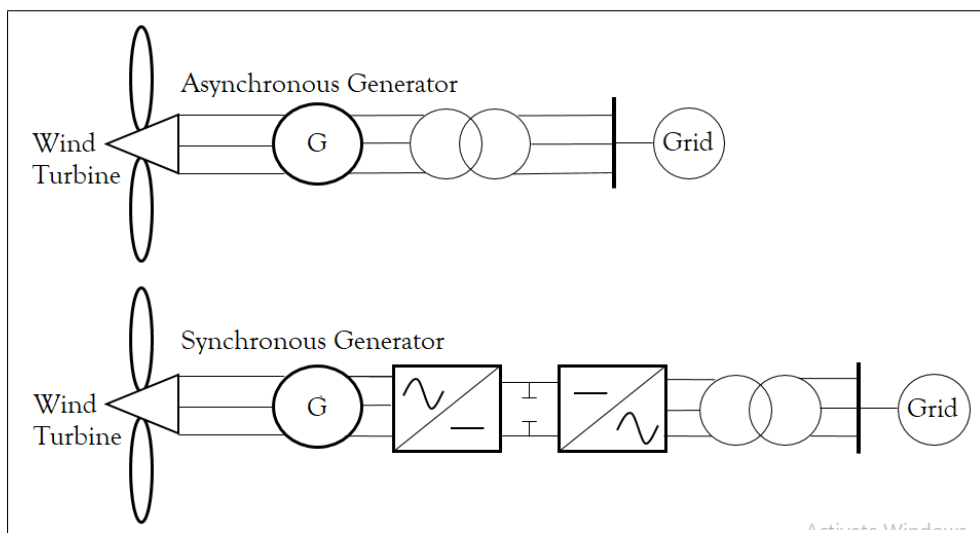


Figure 2.6: Wind turbine connection configurations. Adapted from [1].

When utilizing wind turbines within a microgrid its penetration level should be determined according to certain static (such as losses, loadability and voltage profile) and dynamic (such as post-fault voltage recovery) issues faced.

This method of electricity generation is very appealing as it decreases fossil fuel reliability and increases economical operation of a network. Application of wind turbines in a microgrid rely on the availability of wind and has the ability to adversely effect voltage stability [15].

### **Energy storage system**

ESSs mitigates the variability of RERs in a network. A ESS can be utilized for balancing power demand during fast transient disturbances due to their response time constants being smaller than standard DG sources (diesel generators). Storage charge and discharge can be used to manage energy costs when the time of tariffs are used by the electrical utility. Including an ESS does not only provide smoother transition conditions for the system (islanded to grid-connected and vice versa) but provides a certain amount in network resilience when working with unexpected loading conditions [13].

Variants of ESS that are suitable for microgrids are discussed further in this subsection.

**Battery bank -** Batteries or battery banks utilize chemical methods of storing energy. Currently, this is a rapidly improving field with many varieties producing different benefits and performance levels that should be taken into account when designing a microgrid. Some of these chemical variants are lead-acid, nickel-cadmium, lithium-ion, sodium sulfur and vanadium redox flow batteries.

- **Lead-acid batteries:** Are a tried and trusted technology with low financial cost and high reliability. There are various negatives in utilizing them as they have low specific energy and power, a short lifetime compared to other batteries available and cause a significant amount of pollution during production and retirement (if not disposed of correctly).
- **Nickel-cadmium batteries:** Have high efficiency and long lifetime but their charge retention is poor and their capacity steadily decreases over time. Combined with

restrictions by the European Union (EU), due to heavy metal pollution caused by these batteries, their use in microgrids might be viewed with a certain amount of scrutiny.

- **Lithium-ion batteries:** Have various positives such as high specific energy and power, good charge retention and produces little pollution. Their lifetime may be drastically decreased through mismanagement (such as poor temperature control of battery), control of higher capacity battery banks tend to be more difficult than with some other variants of batteries and manufacturing and maintenance cost are very high. Currently, Lithium-ion batteries are subject to a variety of research and development studies which should improve certain issues such as cost and reliability in the near future.
- **Sodium sulfur batteries:** These batteries have high energy density and high efficiency. Their smaller size compared to other competitors such as lead-acid batteries make them easy to install and further development make them promising contenders for use in microgrids.
- **Flow batteries:** Flow batteries possess a lot of potential as they can be purposely designed for the location of use. They possess 100% discharge capabilities, long lifetime, easy methods of increasing capacity and has a rated power that is independent of capacity. Currently, these batteries are not as widely available as some of the other variants and costs might be high but will improve as the need for such batteries increase.

Deep discharging, over- and undercharging may be damaging to batteries within a microgrid. To increase operable lifespan it is thus recommended to only have one full charge and discharge cycle for batteries per 24 hour period. Note that this does not mean complete discharge or charge should occur once off but rather that the battery capacity should be set as a total limit for both charging and discharging within this period [16].

**Supercapacitor** - A supercapacitor, as with a normal capacitor, uses electromagnetic principles to store energy. Supercapacitors are developed based on the electromagnetic double-layer theory, making it a double layer capacitor when charged. A supercapacitor's structure allows for high amounts of pulse power to be stored but does not provide long duration storage capacity (due to low voltage withstand capabilities and leakage currents). They are ideally used for short-time high-load shifting, support for short instantaneous voltage disturbances and for certain high power demand scenarios such as large motor startups [1].

**Flywheel** - A flywheel is a physical method of storing energy. Comprised from various parts, such as a high-speed flywheel, bearing support system, a power converter, control system and finally a motor/generator, allows the system to convert electrical energy to mechanical and back again. This is done by using excess energy when available to spin up the flywheel to high speeds and using that stored momentum as the generator's prime mover when the need arises. This method of energy storage is mostly used for an emergency power supply, load shifting, frequency control and transition of system operating modes [1].

### 2.2.2 Microgrid operation - Control hierarchy

A microgrid is a complex system with various different operational units and objectives, requiring a control system that can utilize these units for economic efficiency and ensure reliable and quality power is supplied. A microgrid will use different strategies and prioritize objectives depending on its current operation mode (grid connected or islanded) [13].

Microgrid control can be viewed in a hierarchical manner [13]. Typically the system constitutes a Primary, Secondary and Tertiary level of control as shown in figure 2.7. Tertiary level control is done by the utility and pertains to clusters of microgrids as discussed in [11] and not discussed further within this section.

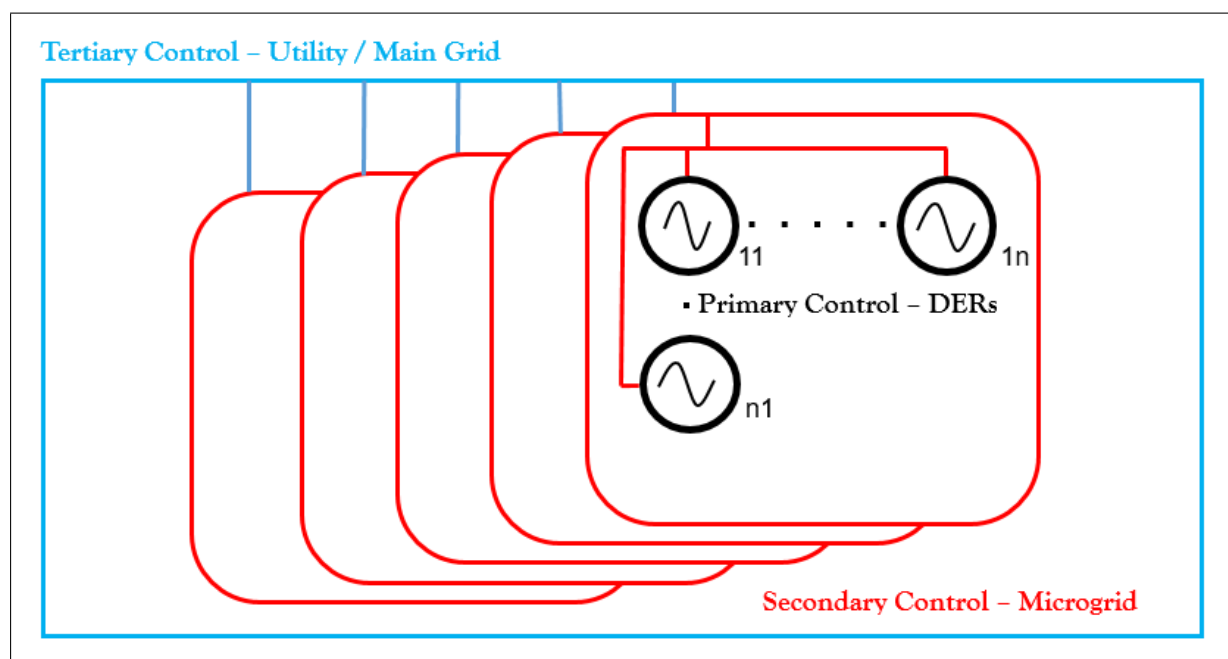


Figure 2.7: Typical microgrid control hierarchy. Adapted from [3].

Primary control is the local control which is the first level in the hierarchy and has the fastest response. Primary control relies on local measurements and does not require any external inputs. Islanding detection, output control and power sharing control is classified as primary control [3,26].

Categories for primary control can be divided into Voltage-Source Inverter (VSI)s that act as interface and management for DC sources, and power sharing which control AC sources, such as generators.

A VSI in a microgrid can consist out of a DG power sharing controller (responsible for active and reactive power mismatch in the microgrid) and an inverter output controller (regulating the output voltage and current). The most common design for the inverter output controller typically utilizes PI controllers, with feed-forward compensation implemented in an outer loop for voltage control and an inner loop for current regulation [3].

Power sharing can be classified into Droop-Based or Non-Droop-Based control meth-

ods [17].

Droop-based methods are derived from the power balance principle used in large interconnected networks on synchronous generators. It makes use of the relation between active power and frequency (an imbalance between input mechanical power and output active power translates into a deviation of frequency) as well as reactive power and output voltage.

The relation between these parameters can be used to derive a droop characteristic as shown in figure 2.8. This graph guides the adjustment of the synchronous unit connected to the network. Different system requirements and structures will cause different droop characteristics [3,27–29]. Commonly used droop control equations are,

$$\omega_i = \omega_0 - m_i P_i \quad (2.4)$$

and,

$$U_i = U_0 - n_i Q_i \quad (2.5)$$

with  $\omega_i$  and  $U_i$  as frequency and voltage outputs of DG units,  $\omega_0$  and  $U_0$  as frequency and voltage amplitude references,  $m_i$  and  $n_i$  as droop coefficients, and finally  $P_i$  and  $Q_i$  as active and reactive power outputs of the respective DGs.

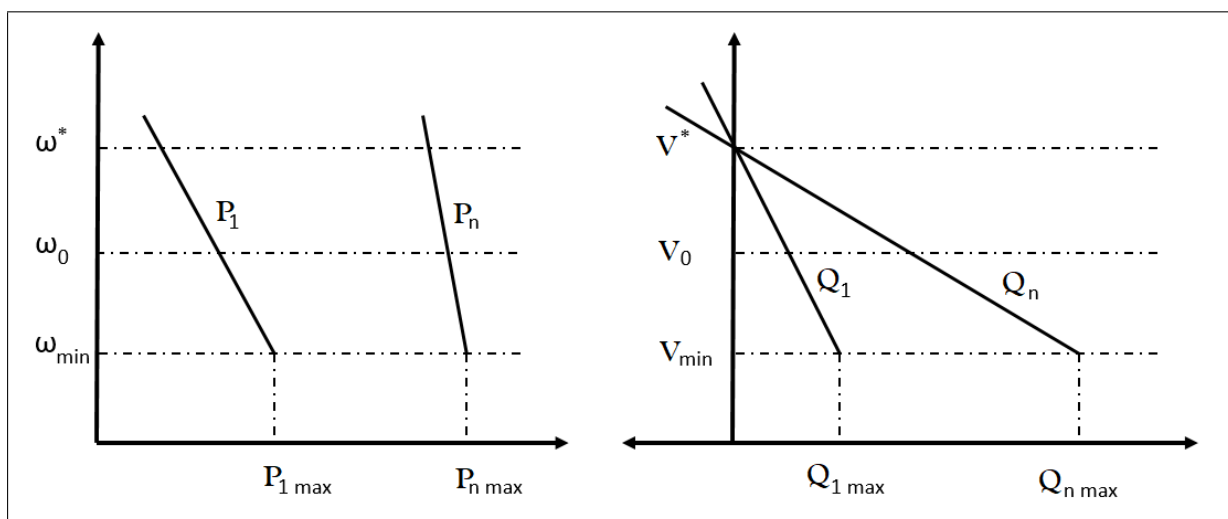


Figure 2.8: Droop Characteristics. Adapted from [3].

For Non-Droop-Based methods various possible solutions can be implemented [3,17]. A centralized controller can accumulate the various DER unit load current values and then allocate new DER values. In this instance, an outer loop simultaneously controls system voltage.

A master-slave approach can be followed, where a single dominant DG unit is used to maintain the system voltage while all other units supply the load [13]. A similar method to the master-slave can be implemented by a DG unit using a nested control loop controlling the voltage at the PCC.

Additional decentralization of voltage control can be achieved with a centralized controller while local controllers handle harmonic and imbalance rejection.

Secondary control's (Energy Management System) main objective is the reliable, secure and economical operation of the microgrid in stand-alone or islanded mode. This is achieved by determining each DG unit's optimal Unit Commitment (UC) according to various objectives [3,10,12].

Secondary control is the highest hierarchical level within a microgrid and operates on a slower time frame than that of the primary control. This allows time for complex calculations, decouples the two levels of control from one another and reduces communication bandwidth through the use of sampled variable measurement values. The two architectures typically used by the secondary control system is a centralized or decentralized approach. Regardless of architecture both ESS and communication methods should be taken into account when addressing the Energy Management System (EMS) of a microgrid. ESS designed for long supplementary operating periods can balance demand-supply equation and maintain dispatchable DG units at maximum efficiency [3,10].

For a centralized approach, a single central controller is provided with all of the possibly relevant information (measurements, operational limits etc.) from every DER unit, load, forecasting system (i.e. weather) and network it is connected to. Using these measurements, in conjunction with its prioritized objectives, it determines and dispatches

the individual DER unit's optimal UC. Various strategies to determine the UC of the system exist. Note that this list includes some of the more popular strategies but does not include all the possible approaches [3].

Optimal dispatch is typically used in smaller microgrids with limited amounts of generation units. Various scenarios are taken into account for which the optimal operation is calculated and analyzed off-line and then added to a lookup table. As the conditions of the microgrid and network change, the lookup table can be instantly referenced to determine how the microgrid should react. Note that the number of possible scenarios on more complex or large microgrid networks can become overwhelming for this method. Further, the introduction of a ESS can make the necessary calculations more complex as it adds a time dependency moving the focus away from solely taking a particular demand scenario into account.

Bidding, which is seen as the most typical method of centralized microgrid control, utilizes cost functions and operating limits of the various DG units transferred to the central controller to determine the appropriate system operation. It is possible to implement a more active method of bidding by letting consumers and generators bid for their production and consumption.

Non-model-based approaches are attractive for their greater adaptive properties and the robustness they provide to the network. Typical non-model-based approaches include fuzzy and Artificial Neural Network (ANN) controllers [3].

Model Predictive Control (MPC) formulates and solves an optimization problem at each discrete time-step and allows the implementation of control actions that anticipate future events. A control sequence is calculated for the whole horizon such that the selected objectives are minimized, but only the next step in the control sequence is implemented, whereafter the process is repeated for the next increment of time.

Day-Ahead Economic Load Dispatch can be utilized for sporadic DG units and an ESS, where the programmed dispatch for the system is updated every 15 minutes so that voltages are kept at acceptable values while the unit dispatch is kept as close as

possible to the predetermined values.

The main goal of a decentralized approach to secondary control is to add a missing level of autonomy to the EMS [3]. This desired autonomy is achieved through the use of yet another hierarchical control structure with three different levels namely the Distribution Network Operator (DNO), Microgrid Central Controller (MGCC) and DER Local Controller (LC).

A DNO acts as the microgrid's interface with the distribution network and categorized as part of the tertiary level control. The MGCC acts as aggregated coordinator of all DER units and loads connected to the microgrid network and ultimately responsible for the reliable and economic operation of the system as well as interacting with the main grid. LCs control the various DER units connected to the system doing necessary local measurement, analyses and control. All these actions occur while communicating with the MGCC and other LCs on the network to allow coordinated completion of any local and global objectives set by the main controller.

This interaction between the MGCC and LCs is critical as it not only sends and receives objectives and measurements but communicates expectations, requests and offers of service as well as any other information/knowledge critical for the operation of the microgrid. Although there are different ways to implement a decentralized approach, according to the literature a Multi-Agent System (MAS) framework has primarily been used [3, 10, 17].

### 2.2.3 Microgrid standards

The development of microgrid specific standards is currently ongoing throughout the world by a variety of societies. Not all of the following standards focus solely on or cover all aspects of microgrid or DER connection and operation, but provide a stable base for understanding the status of standard development.

Some examples of region-specific standards are:

- The European Committee for Electrotechnical Standardization (CENELEC) issued *Requirements for the Connection of Microgenerators in Parallel with Public Low-voltage Distribution Networks*.
- The ER G75/1 standard, *Recommendations for the Connection of Embedded Generating Plant to Public Distribution Systems above 20 kV or with Outputs over 5 MW*, issued by the United Kingdom.
- A formulated guide by the Business Council of Australia named *Guide to Connection of Microsources to the National Electric Power Market*.

Though the widespread development of these regional standards and guides that all pertain to microgrids are a clear indication of the worldwide focus shift to the implantation of microgrids and the realization of a Smart Grid (SG).

The standards taken into account for this research are those issued and under development by the international societies namely Institute of Electrical and Electronics Engineers (IEEE) and International Electrotechnical Commission (IEC), because no regional standard, specifically focusing on microgrids, has yet been adapted in South Africa.

The two most notable standards are the IEEE 1547 and IEEE 2030.

**IEEE 1547 -** Traditionally transmission and distribution networks were designed for unidirectional power flow. This changed with the advancements by distributed generation in the form of renewable energy, that made them more cost-effective and allowing consumers to become suppliers of electrical energy. The IEEE 1547 series of standards was developed to provide a cohesive set of requirements, recommended practices and guidance for standardizing the interconnection of the rising amount of DERs that were and are being connected to the power network [30]. Table 2.2 lists the IEEE 1547 series of standards.

Table 2.2: IEEE 1547 standard series

| Standard           | Description                                                                                                                                                  |
|--------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------|
| IEEE 1547 (2003)   | <i>Standard for Interconnecting Distributed Resources with Electrical Power Systems</i>                                                                      |
| IEEE 1547.1 (2005) | <i>Standard for Conformance Tests Procedures of Equipment Interconnecting Distributed Resources with Electrical Power Systems</i>                            |
| IEEE 1547.2 (2008) | <i>Application Guide for IEEE 1547</i>                                                                                                                       |
| IEEE 1547.3 (2007) | <i>Guide for Monitoring Information Exchange, and Control of Distributed Resources with Electric Power Systems</i>                                           |
| IEEE 1547.4 (2011) | <i>Guide for Design, Operation and Integration of Distributed Resource Island Systems with Electric Power Systems</i>                                        |
| IEEE 1547.6 (2011) | <i>Recommended Practice for Interconnecting Distributed Resources with Electric Power Systems Distribution Secondary Networks</i>                            |
| IEEE 1547.7 (2013) | <i>Guide to Conducting Distribution Impact Studies of Distributed Resource Interconnection</i>                                                               |
| IEEE 1547.8        | <i>Practice for Establishing Methods and Procedures that Provide Supplemental Support for Implementation Strategies for Expanded Use of IEEE 1547 - 2003</i> |

The IEEE 1547 (2003) acts as the base for this series and was designed to be technology neutral while being applicable to all DERs that have an aggregated capacity below 10 MVA [30]. This standard provides the minimum functional requirements to help ensure technically sound interconnection of all DERs.

As the series develops, different aspects pertaining to DER are improved. Specifically, IEEE 1547.4 is of special interest as it focuses on the design and implementation of DER within a microgrid. Note that the IEEE 1547.4 is specifically for microgrid systems that can island at will and can reconnect to power network when necessary, permanent islanded systems are not included in this research.

The various concerns surrounding microgrid (distributed resource island system) planning, operation and configuration are discussed in the standard. Further islanding

configurations, power quality regulation, system planning, component implementation and compatibility are included in [31]. In conclusion, the IEEE 1547 was at the time of writing the most authoritative document dealing with smart microgrids.

**IEEE 2030 -** With the IEEE 1547 focusing on the interconnectivity of DERs the IEEE 2030 focuses on the interoperability of the various systems, components, applications or devices that would be found within a Smart Grid, such as the smart microgrid. The IEEE 2030 provides a vast knowledge base on terminology, characteristics and Smart Grid functional performance standards. From this, a Smart Grid Interoperability Model (with a focus on interfaces, data flow and logical connections) is formed which defines architectural perspectives for power systems as well as communication and information technology [30]. Table 2.3 lists the IEEE 2030 series of standards.

Table 2.3: IEEE 2030 standard series

| Standard         | Description                                                                                                                                                          |
|------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| IEEE 2030 (2011) | <i>Guide for Smart Grid Interoperability of Energy Technology and Information Technology Operation with Electric Power System, and End-Use Application and Loads</i> |
| IEEE 2030.1      | <i>Guide for Electric-Source Transportation Infrastructure</i>                                                                                                       |
| IEEE 2030.2      | <i>Guide for the Interoperability of Energy Storage Systems Integrated with the Electric Power Infrastructure</i>                                                    |
| IEEE 2030.3      | <i>Standard for Test Procedures for Electric Energy Storage Equipment and Systems for Electric Power System Applications</i>                                         |

With the IEEE 2030 still being a relatively new series of standards, various drafts and revisions are in development. Staying up to date with this series is necessary when trying to implement microgrids as part of the planned SG future.

Other international standards that should be taken into account are:

- The IEC TS 62257 *Recommendations for Small Renewable Energy and Hybrid Systems for Rural Electrification*.

- The IEEE 446-1995 *Recommended Practice for emergency and Standby Power Systems for Industrial and Commercial Applications*
- The IEC 61850 *Communication networks and systems in substations*

Although not pertaining specifically to microgrids the following South African standards should be taken into account when connecting DERs to the national grid:

- The NRS 048 *Electricity Supply - Quality of Supply* (further discussed in chapter 4)
- The NRS 097 *Grid Interconnection of Embedded Generation*
- The South African Grid Code

## 2.3 Dynamic modelling and response

As discussed in section 2.2 there are a variety of reasons for implementing a microgrid [8]. Despite all these benefits and its smaller scale, microgrids have complexities similar to large scale power systems.

Microgrid dynamic modelling is made difficult by the following characteristics [16]:

- Short response time of the various DERs in conjunction with their close proximity to one another.
- Single phase generation and loading cause possible unbalance phenomena.
- Insufficient energy storage and the lack of sufficient inertia as found in the public network.
- Uncertainty in accurate equivalent network models due to diversity in DER solutions.
- Topology and network design uncertainties as each microgrid is typically set up differently.

### 2.3.1 Stability

Understanding and controlling the dynamic response of a microgrid is to ensure its stable operation during different operating modes and objectives. Stability analysis is divided into different categories to simplify the process of determining the root cause analysis of stability concerns [16, 18].

Small-signal or steady-state stability is related to active power limits within DGs, continuous load switching and feedback systems. Transient stability problems are caused due to any large disturbances to the network and when resolved allows operation after such a disturbance. Voltage and frequency stability issues can be caused by a variety of elements within the system such as reactive power limits of the DGs, specific load dynamics and tap changers [16]. These different factors contribute differently to instability depending on different microgrid topologies/implementations.

Small-signal stability can be improved through the use of supplementary control loops, stabilizers and/or coordinated control of the various DERs within the microgrid. Transient stability can be improved through the use of an ESS, load shedding and/or adaptive protection devices. Voltage stability can be improved through the use of individual DG voltage regulation, reactive power compensation, advanced load control and/or modifying the current limiters on DERs [18]. Figure 2.9 summarize different stability problems and methods to mitigate instability.

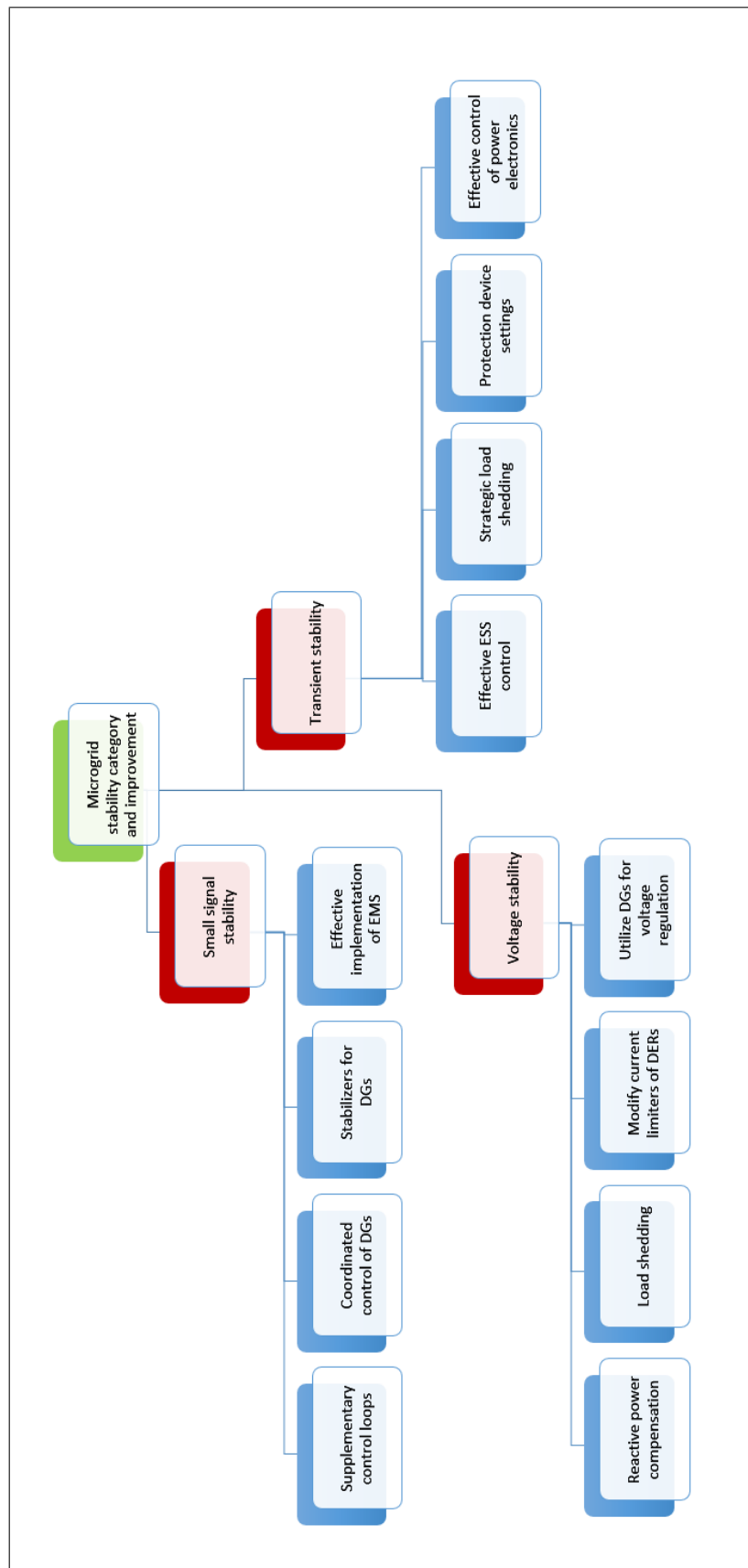


Figure 2.9: Stability issue classification and solution schematic

### 2.3.2 Power Quality

The referred to PQ concepts pertaining to this research are summarized in table 2.4 [19]. Note that the classification of PQ events are not globally uniform and certain parameters may differ depending on the authoritative standard in a region.

Voltage-sensitive loads (Variable Speed Drive (VSD)), increase the need for good PQ. Local control in microgrids on system frequency, voltage and loading allow PQ to be better controlled than in public networks. Combined with the fast response provided by the inclusion of an ESS provides answers to possible PQ concerns. Active voltage conditioning can further improve PQ in a microgrid [12].

Having a microgrid grid-tied to a utility does not only provide the benefit of energy sharing but provides a PQ benefit, as any shortfall experienced by the microgrid can be supplemented by the utility. This should be utilized to a minimum as a microgrid should be designed to be self-sufficient and any PQ issues on the utility's side of the network (upstream) will have an effect on the microgrid (downstream).

If the need arises to isolate the microgrid's PQ events from those of the utility, a Microgrid Power Quality Conditioner (MPQC) is recommended. This MPQC consists of a shunt and series converter that can be operated independently from one another. The shunt converter is controlled in voltage source mode and by means of active voltage conditioning, PQ can be controlled. The series converter is controlled in either current source mode to produce balanced sinusoidal line current, or as a large impedance to limit line current during voltage sag [20].

A microgrid in islanded mode has a much higher system impedance and could be susceptible to worse PQ compared to when grid tied. The PQ within this islanded system should be maintained, preferably without installing additional power-conditioning equipment. This can only be done by utilizing a coordinating/supervisory algorithm to ensure cooperative compensation is done by the various DERs connected. Within literature, various algorithms and strategies can be found [13,20].

Table 2.4: Power quality trends and events

| Problem                 | Description                                                                                                                                                                                                                                                                                                                                                                                                                                       |
|-------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Voltage dip/sag         | A decrease of 10-90% in nominal voltage from 0.01 seconds (in a 50 Hz network) to 1 minute.<br>This may cause a malfunction in information technology equipment, tripping of contactors/relays and the disconnection and loss of efficiency in electric rotating machines.                                                                                                                                                                        |
| Short interruption      | Complete interruption of electrical supply lasting more than 3 seconds (National Regulatory Standard (NRS) 048 classification).<br>This may cause tripping of protection devices, stoppage of sensitive equipment and malfunction of data processing equipment.                                                                                                                                                                                   |
| Sustained interruption  | Complete interruption of electrical supply lasting more than 1 to 5 minutes, depending on the network (NRS 048 classification).<br>This will cause stoppage of all equipment.                                                                                                                                                                                                                                                                     |
| Voltage spike/transient | Very fast variation of voltage value lasting from a few micro- to a few milliseconds.<br>This may cause the destruction of electronic components and isolation, electromagnetic interference and data processing errors/loss.                                                                                                                                                                                                                     |
| Voltage swell           | Momentary increase of voltage above normal tolerance (typically 10% of nominal value) that lasts between one cycle and a few seconds.<br>If too high this may cause stoppage/damage to sensitive equipment, data loss and flickering of light sources.                                                                                                                                                                                            |
| Harmonic distortion     | Voltage waveform deforms to a non-sinusoidal shape due to the presence of other sinusoidal waves with frequency magnitudes that are variables of the base frequency.<br>This increases the chance for resonance, neutral overload in a 3-phase system, overheating of cables and equipment, errors in measurements, loss of efficiency in electrical machines, interference in communication systems and nuisance tripping of thermal protection. |
| Voltage flicker         | A slow oscillation of voltage magnitude (between 0 and 30 Hz).<br>The flickering induced in lighting causes the impression of unsteadiness in visual perception and may have a medical effect on persons that are exposed.                                                                                                                                                                                                                        |
| Voltage unbalance       | The voltage magnitudes and/or phase-angle differences between phases in a three-phase system are not equal.<br>This indicates the presence of the negative sequence which affects the operation of various machines.                                                                                                                                                                                                                              |

If needed additional active voltage conditioning equipment can supplement reactive power compensation with superior response time to other conventional methods.

IEEE 1159 and IEC 61000 series are standards pertaining to international power quality. The IEC 61000 is an enforced standard with the IEEE 1159 being of an informative nature. South Africa's own power quality compliance document is the NRS 048 and discussed in chapter 4. The NRS 048 classification of voltage dip events is depicted in figure 2.10.

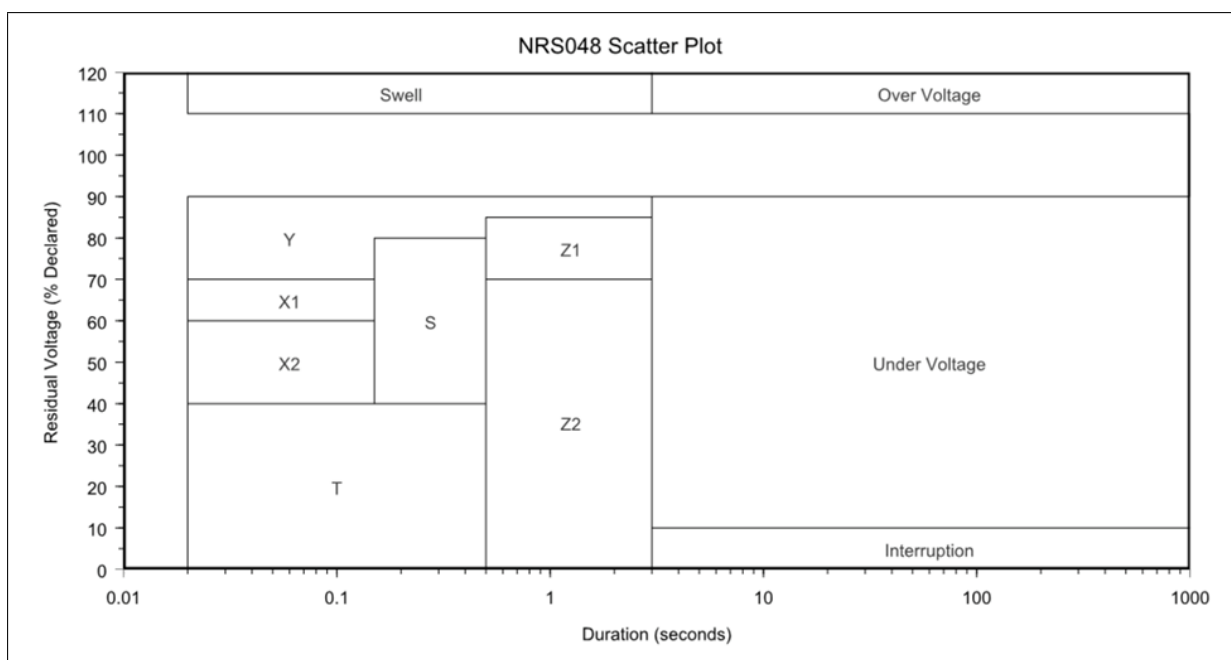


Figure 2.10: NRS 048 voltage event classification. Generated in Osprey Lite.

Note that although the individual quality of power produced by a DER is important, the value of proper secondary level control and the utilization of a strategy such as a MAS, Particle Swarm Optimization (PSO) or ANN is significant in terms of PQ as various sources suggest [12, 16, 20].

## 2.4 Conclusion

Microgrids are an important component of the electrical distribution network infrastructure of the future. Chapter 2 analysed microgrid components, control strategies and how a smart microgrid can be realized. Technical standards on microgrids were introduced and discussed in the context of the research undertaken in this dissertation. Quality of power in microgrids can be a concern and how to contain these concerns were briefly discussed.

Within the context of theoretical principals, the modelling of a microgrid is analyzed next. Knowledge obtained in this chapter is used to interpret practical data obtained from DERs installed in a Low Voltage (LV) microgrid.

# Chapter 3

## Model development and verification

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*Chapter 3 derives a functional microgrid model. Supporting literature is used in model development. Section 3.4 describes the mathematical modelling of different DERs. Section 3.6 verifies the model.*

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### 3.1 Introduction

A representative model is important for microgrid development and to accurately predict performance. Simulation environment selection is the first step, and although various possibilities exist, an objective project specific approach should be used to identify the most viable simulation environment. Mathematical models and methods have to be validated and incorporated to produce accurate results.

This validated model is then applied in designing and operating a microgrid.

## 3.2 Simulation environment

There are various approaches to microgrid modelling and simulation. When deciding on a simulation environment the following criteria should be taken into account.

1. Modelling objectives.

- Steady state load flow analysis or a transient study?
- Simulation time steps and period?
- The level of complexity taken into account i.e. Should sub-transient reactance be taken into account within the generator model?

2. Simulation software.

- Is peer reviewed literature available to better understand the scope and limitations of simulation software?
- Cost?
- Hardware requirements?
- Availability of developer and user based support?

3. Learning curve

- How difficult will it be to create a representative model that produces credible results?

The following options were available to the researcher and briefly evaluated below:

ATP, MATLAB with Simulink extension, DIgSILENT PowerFactory or a DIgSILENT/MATLAB hybrid.

### 3.2.1 ATP and ATPDraw

ATPDraw is merely the mouse-driven pre-processor of the Alternative Transient Program (ATP) simulation environment which is a version of the Electromagnetic Transients

Program (EMTP) developed in the public domain at Bonneville Power Administration (BPA) in the 1960s [32]. The ATP/EMT simulation environment is widely trusted and used for various electromechanical and electromagnetic simulations including the modelling and dynamic simulation of microgrids such as in [33–35].

### 3.2.2 MATLAB and Simulink environment

MATLAB is a powerful numerical analysis environment with various add-on products such as Simulink (a graphical environment for modelling and simulating dynamic systems) [36] and Simscape that provides the capability to create and simulate physical system components within the Simulink environment.

The above structure provides two main approaches to modelling a microgrid within MATLAB. The first is to model the network components and control within a MATLAB script using MATLAB programming language and differential equations for the various components such as synchronous generators. This algorithm-based approach is described in [37–39].

Modelling by differential equations should be accurate but requires extensive understanding of the mathematics needed to model a specific microgrid component. Creating a complex network and control systems can be a challenge.

The second approach is using Simscape within and in conjunction with Simulink. Examples can be found in [21, 40, 41].

### 3.2.3 DIgSILENT PowerFactory environment

As the acronym for DIgSILENT, “Digital Simulation of Electrical Networks”, suggests PowerFactory is a digital engineering tool specifically developed for analysis of industrial, distribution and transmission power systems [42]. The accuracy of results is verified through the worldwide implementation that PowerFactory enjoys.

PowerFactory is a powerful tool that can be used for a variety of different system applications such as described in [22]. Any power system created can be controlled through the use of PowerFactory's own DIgSILENT Simulation Language (DSL) or DIgSILENT Programming Language (DPL), Python, and finally C or MATLAB external interfaces. Depending on the type of simulation done, the control configuration may differ. The focus of this dissertation is the dynamic response of a power system and thus PowerFactory's RMS (used for mid- and long-term transient studies) and EMT (used for short-term transient studies) simulations used in [15, 43–46], to simulate microgrids, are of interest.

### 3.2.4 DIgSILENT/MATLAB hybrid environment

It is possible to use PowerFactory in conjunction with MATLAB and Simulink to create a fully functioning microgrid model. This hybrid approach uses the specialized PowerFactory environment for power system calculations while outsourcing the control of this power system to the more well-known control environment of Simulink. This approach is used in [47–49].

The extent of control done by MATLAB is dependent on user preference and the detailed process on how this functionality is used can be found in [22]. Figure 3.1 depicts a graphical summary on the typical communication flow between these two simulation environments.

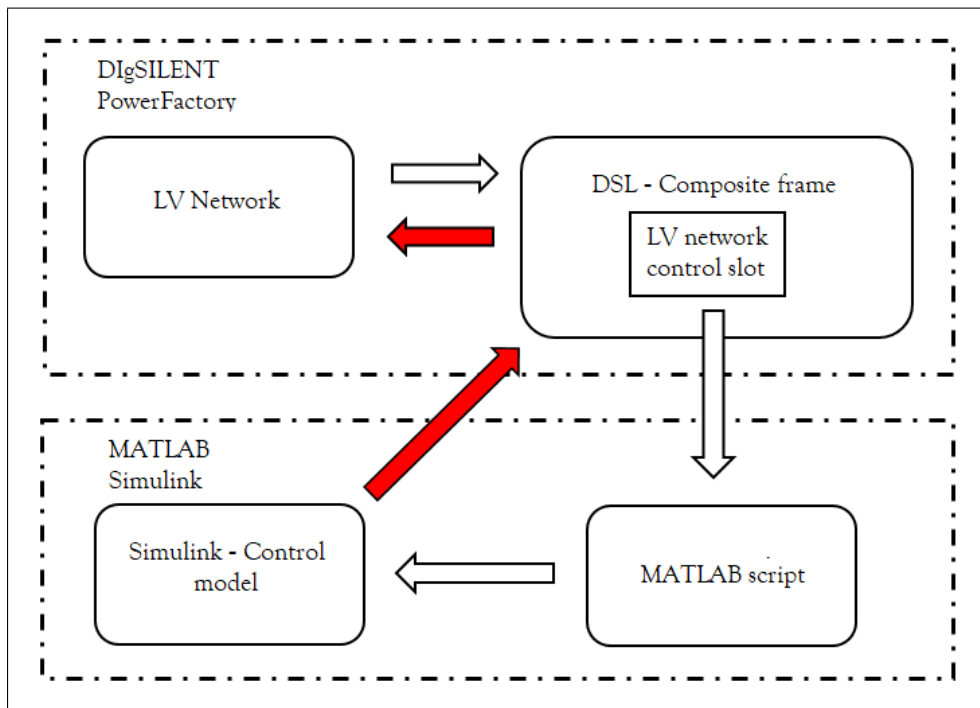


Figure 3.1: DIgSILENT/MATLAB communication schematic

### 3.2.5 Comparison and selection

Note that the results may be subjective to some extent as it is difficult to compare the various simulation environments on a completely equivalent level. Depending on the hardware used as well as how efficient a model has been constructed the performance may differ from user to user.

**Availability -** Availability of the software is important as deliverables and the project budget have a large impact on the choice being made. DIgSILENT PowerFactory is ranked last in this research project last due to its large licensing costs as many smaller businesses and consultants may not be able to justify. It is important to note that most of the larger consulting engineering firms as well as utilities use DIgSILENT.

MATLAB is placed second, because of being more affordable. Due to the nature of MATLAB, it is relatively accessible in academic circles but is not commonly found in

the commercial engineering environments.

ATP/ATPDraw is the winner as it is completely free, widely available and used frequently within the power engineering community both commercially and academically.

**Learning curve -** As engineering hours are typically expensive, it is important to take the amount of time needed to learn a new simulation environment into account. Although ATPDraw drastically increases the user-friendliness of the ATP environment, its old punched card-based approach to creating models may make the entire modelling and simulating experience frustrating and difficult for a beginner and even adept users and thus it is placed last.

PowerFactory is ranked second as it has a relatively bizarre model structure (especially when using DSL) for beginners and a user manual that tends to feel targeted at more adept users. Note that once the user learns the environment creating and simulating models in PowerFactory, is typically faster to construct a complete model than in ATP or MATLAB.

MATLAB is placed first as the language used in its script interface is similar to well-known programming languages such as Python and C. With Simulink and Simscape using a basic drag and drop approach and having a user-friendly search function, creating models are relatively easy. One negative of the Simulink environment is its large diversity of components and its scattered focus, which makes creating the optimal model that works efficiently more challenging.

**Community support -** Having an active and supportive community to assist when struggling with a modelling or simulation problem is a large benefit. DIgSILENT's support centre and knowledge base have limited examples of various model and possible simulation combinations that can be created within the PowerFactory environment and external online support is scarce to find, which places it last in this category.

ATP and EMTP have been actively used for a few decades in the public domain. Many example case studies are available for free, placing it second.

MATLAB wins this category by having an extensive user guide and knowledge base (MathWorks) as well as an active online support base on various forums.

**Simulation speed -** The speed category refers to the time the simulation environment takes to solve a power system problem. MATLAB Simulink environment takes excessive amounts of time compared to the competition, which is expected as the environment is not specifically optimized for power systems, placing it last.

Both ATP and PowerFactory are fast at solving power system problems with working models. PowerFactory wins due to being slightly faster as it is possibly a more stream-line simulation environment than ATP. Note that in this category various factors, such as how efficient a model is built, will have an effect on the outcome and thus this is a subjective result.

**Applicability -** Both ATP and PowerFactory have high applicability when modelling and performing dynamic simulations on microgrids, as both were specifically designed for modelling power systems under both steady-state and transient conditions. They include a method of controlling these models.

PowerFactory has a slight advantage as it has more functions and thus wins.

With MATLAB, Simulink and Simscape it is possible to create and dynamically simulate a microgrid but the simulation environment is not specifically made for simulating power systems. MATLAB and Simulink are easy to use and powerful control modelling software, but as soon as the power network element is included the difficulty increases and performance of the software decreases. In essence, MATLAB is not optimized specifically for power systems and is therefore placed last in terms of applicability.

Table 3.1 summarizes the outcome of the comparison. Once again this is a subjective table with "1" as first and "3" as last in the category. As PowerFactory was available for

Table 3.1: Simulation environment comparison

| Criteria          | ATP | MATLAB | PowerFactory |
|-------------------|-----|--------|--------------|
| Availability      | 1   | 2      | 3            |
| Learning curve    | 3   | 1      | 2            |
| Community support | 2   | 1      | 3            |
| Simulation speed  | 2   | 3      | 1            |
| Applicability     | 1   | 3      | 2            |

this research and the control used focuses mostly on primary level control, DIgSILENT PowerFactory environment was selected. The DIgSILENT/MATLAB hybrid was a close contender due to its ease creating both the power system network and control framework, but to get the initialization and communication working properly proved time-consuming.

### 3.3 Base model construction

In this section, basic configuration on the LV microgrid in question is presented using DIgSILENT PowerFactory. DIgSILENT can be overwhelming for new users. A step-by-step guide to dynamic model implementation was added in Appendix A.

#### 3.3.1 Information procurement

Designing a functional model of a physical system requires data procurement of the system's configuration. The microgrid used for model development is an industrial LV microgrid situated in Gauteng, a province of South Africa with an average demand of 300 kVA and maximum demand of 400 kVA.

Figure 3.2 represents the test site LV network and Medium Voltage (MV) connection to the Ekurhuleni metropolitan municipality's distribution network.

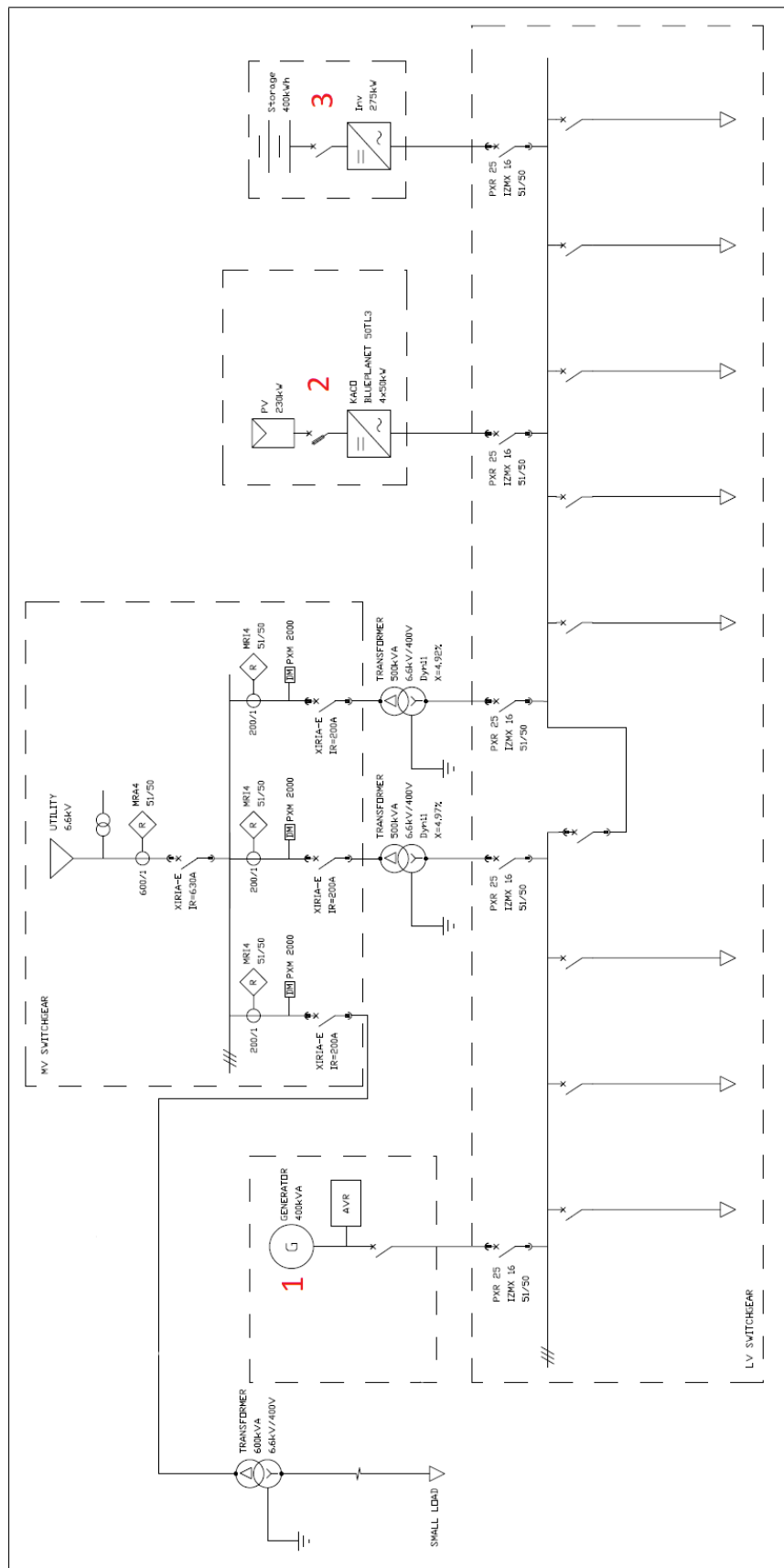


Figure 3.2: Single line diagram of Microgrid LV bus and MV connection to network

The DERs used on the LV bus are:

1. A 400 kVA CAT C13 synchronous generator sized at 400 kVA equipped with an EMCP4 control panel.
2. A PV array of 230 kW connected to four parallel KACO Blueplanet 50TL3 solar inverters rated at 50 kW each.
3. A 275 kW battery bank inverter connected to 200 kWh second life Nissan batteries.

Ideally full technical specifications of the various DERs should be available, but due to strict intellectual property policies of the various companies that supplied the components, detailed technical information was unobtainable.

### **3.3.2 DIgSILENT base implementation**

By using field data on the physical system a base model for the microgrid, as depicted in figure 3.3, was created.

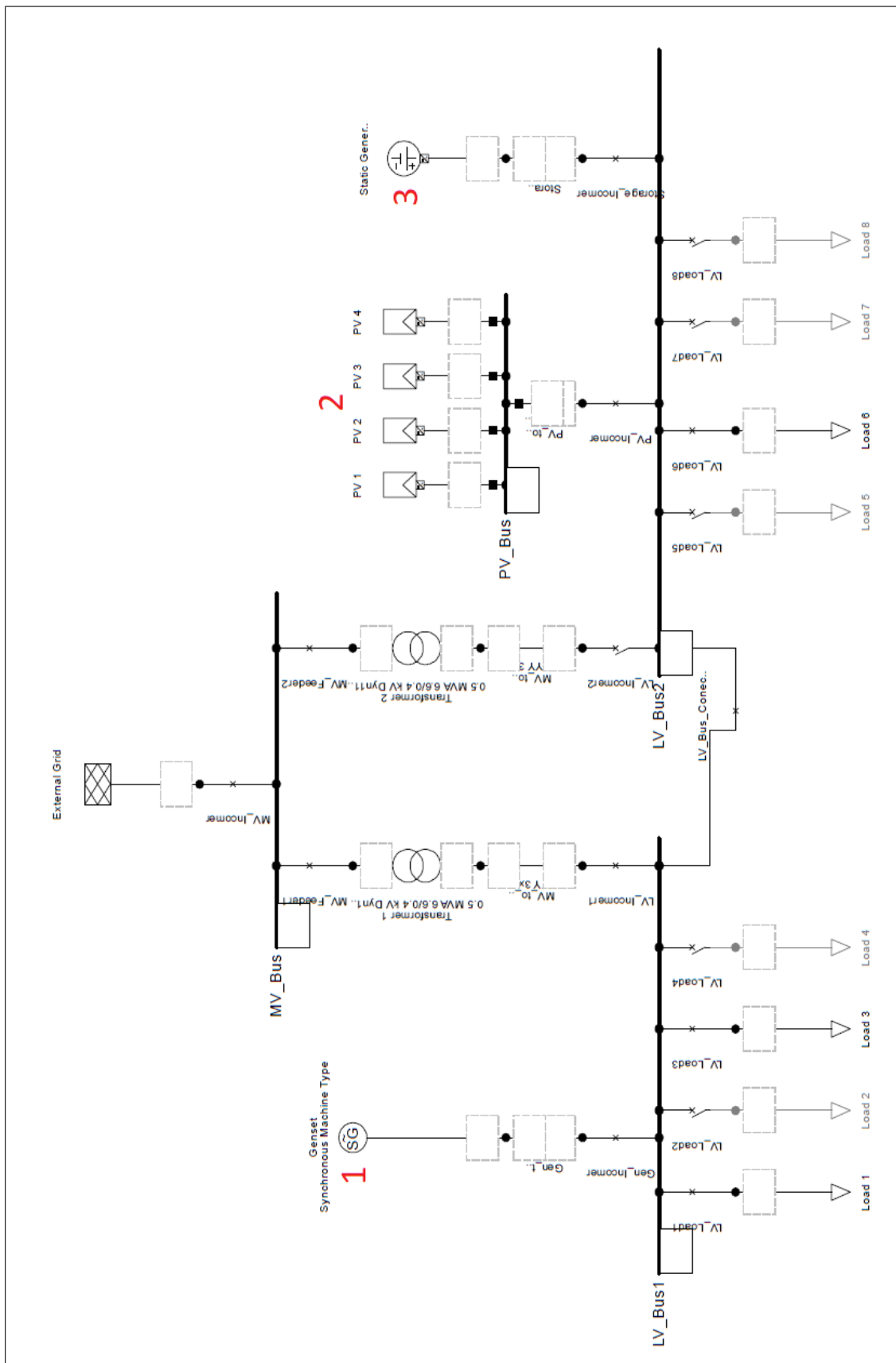


Figure 3.3: Microgrid single line representation within DIgSILENT PowerFactory

The following components were modelled.

1. A 400 kVA three-phase synchronous generator.
2. Four 50 kW three-phase solar inverters.
3. A three-phase inverter connected to a 400 kWh Li-Ion second-life Nissan Leaf batteries.

Real-world loading of the microgrid were incorporated into the model for realistic simulation conditions.

## 3.4 Component modelling

This section presents the modelling of the different microgrid components to be used in the PowerFactory simulation.

### 3.4.1 Clarke and Park transformations

The dq-reference frame ("d" for direct and "q" for quadrature) is firstly introduced. This is done using both Clarke and Park transforms [4].

To start, let  $i_R$ ,  $i_W$  and  $i_B$  be balanced instantaneous three-phase currents:

$$i_R + i_W + i_B = 0. \quad (3.1)$$

These three-phase currents can be used to derive a current space vector in (3.2)

$$\bar{i} = k(i_R + ai_W + a^2i_B), \quad (3.2)$$

with  $k$  being the transformation constant and  $a$  an complex operator, as illustrated by figure 3.4.

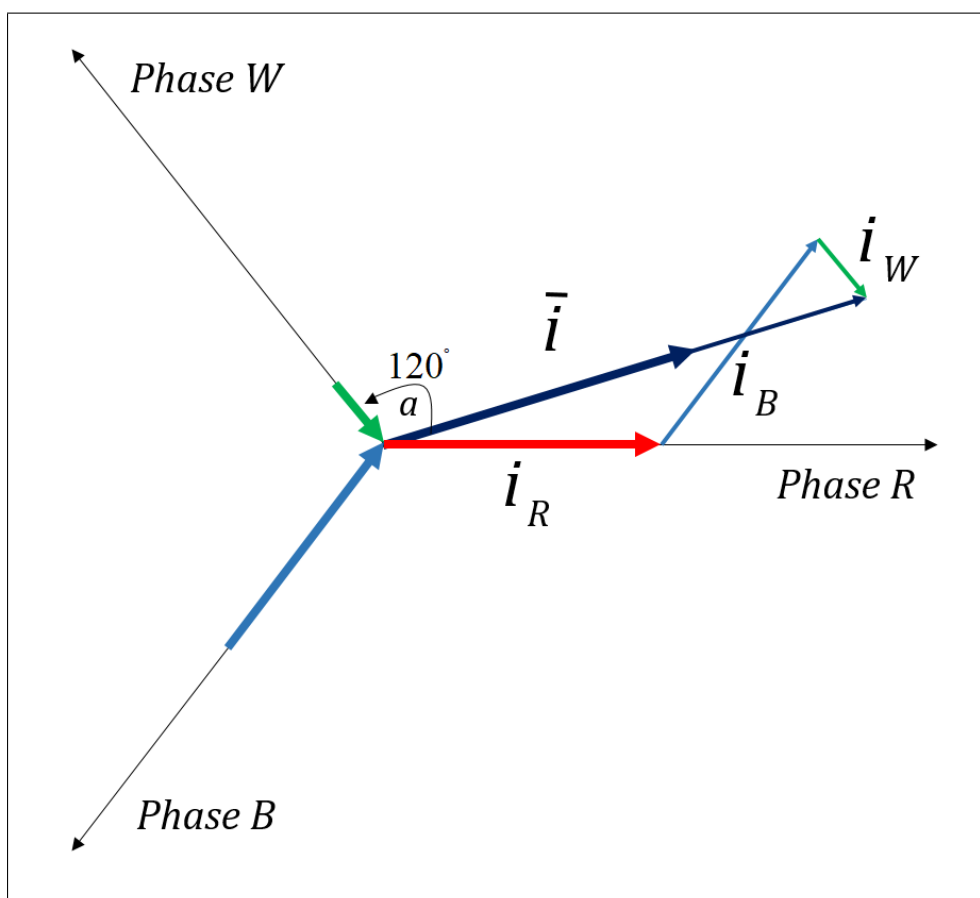


Figure 3.4: Current state vector. Adapted from [4].

In a three-phase system the operator signifies  $a = 1e^{j120}$ ,  $a^2 = 1e^{j240}$  and  $a^3 = 1$ .

The reference frame of the current space vector in figure 3.4 can be simplified by expressing it using the two axis-theory. This theory lets the real part of the space vector be equal to the instantaneous current value,  $i_\alpha$ , on the now defined direct-axis. The imaginary part is then set equal to the current component,  $i_\beta$ , on the quadrature-axis. This transition from 3 to 2 axes is demonstrated in figure 3.5.

Within a symmetrical 3-phase machine the relation between the 3-phase currents and the fictitious quadrature-phase (2-phase) current components  $i_{ff}$  and  $i_{fi}$  can be expressed as,

$$i_\alpha = k(i_R - \frac{1}{2}i_W - \frac{1}{2}i_B) \quad (3.3)$$

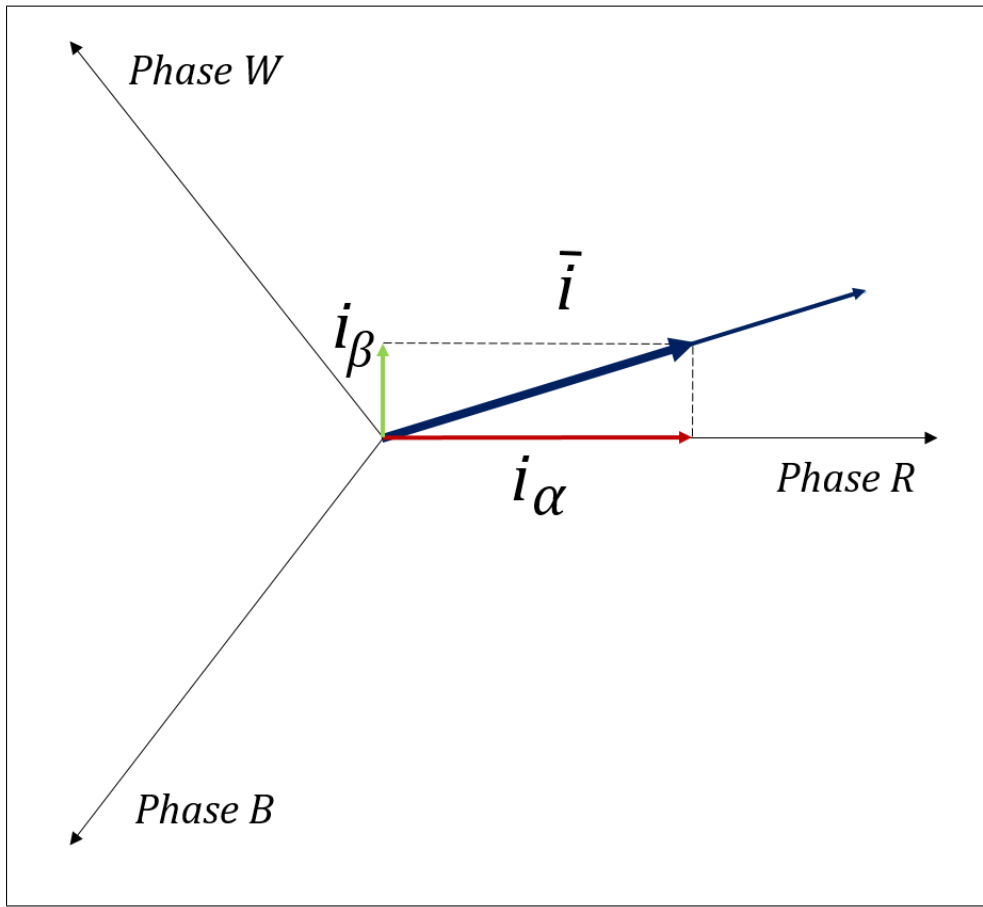


Figure 3.5: Current state vector with 2-axis reference frame. Adapted from [4].

and

$$i_{\beta} = k \frac{\sqrt{3}}{2} (i_W - i_B), \quad (3.4)$$

with,

$$\bar{i} = i_{\alpha} + i_{\beta}. \quad (3.5)$$

For a symmetrical three-phase system the transformation constant  $k$  has a recommended value of  $k = \frac{2}{3}$ . The transformation from 3-phase to a 2-phase system is typically called a Clarke transformation. The stationary reference frame can then be given in terms of three phase currents as,

$$\begin{bmatrix} i_{\alpha} \\ i_{\beta} \end{bmatrix} = \frac{2}{3} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_R \\ i_W \\ i_B \end{bmatrix}, \quad (3.6)$$

with the Clarke matrix as,

$$[Clarke \ matrix] = \frac{2}{3} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix}. \quad (3.7)$$

Current space vector equations can be formulated to change this 2-axis stationary reference frame into one which rotates at a general speed of  $\omega$ . This transformation from a stationary to rotating reference is attained by application of the Park transform. Figure 3.6 depicts this relation between the  $\alpha$  and  $\beta$  axes and the transformed d and q axes (direct and quadrature axes).

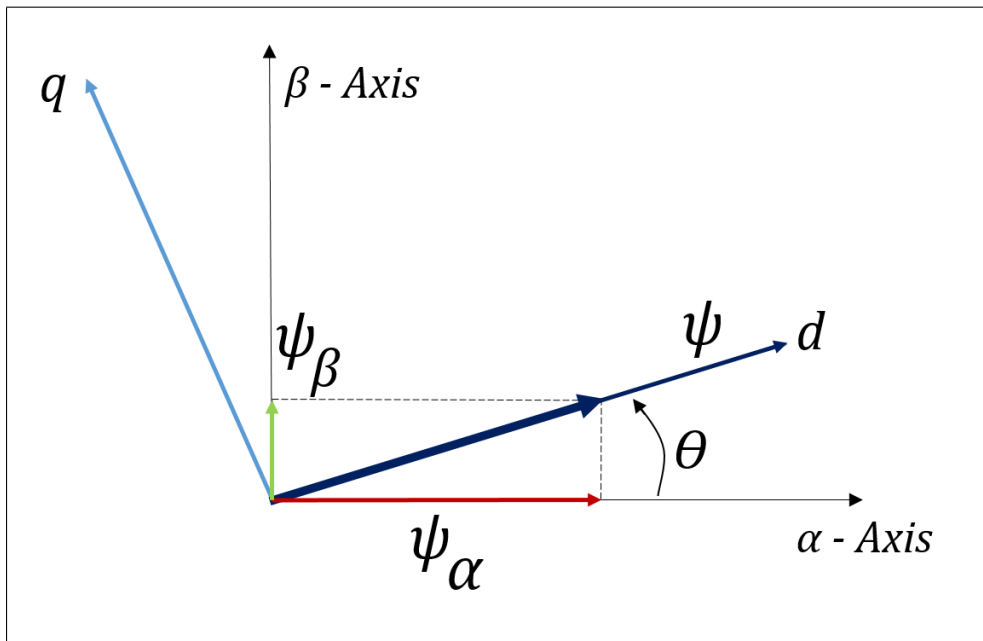


Figure 3.6: Current state vector with rotating reference frame. Adapted from [4].

Let  $\psi$  be a state space vector in figure 3.6 defined in the Clarke and Park plane as:

$$\psi = \psi_\alpha + \psi_\beta \quad (3.8)$$

and,

$$\psi = \psi_d + \psi_q \quad (3.9)$$

The angle  $\theta$  between these vector components are then given by,

$$\sin\theta = \frac{\psi_\beta}{\psi_d} \quad (3.10)$$

and,

$$\cos\theta = \frac{\psi_\alpha}{\psi_d} \quad (3.11)$$

Thus the Park transform from  $\alpha\beta$ -reference frame to dq-reference frame can be defined as,

$$\begin{bmatrix} \text{Park matrix} \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} \quad (3.12)$$

and,

$$\begin{bmatrix} d \\ q \end{bmatrix} = \begin{bmatrix} \text{Park matrix} \end{bmatrix} \begin{bmatrix} \alpha \\ \beta \end{bmatrix}. \quad (3.13)$$

It is possible to transform back to a  $\alpha\beta$ -reference frame using the reverse Park transform and then back to the three-phase reference frame (phase domain) from the  $\alpha\beta$ -reference frame using the reverse Clarke transform [4].

### 3.4.2 Synchronous generator

Figures 3.7 - 3.9 illustrate how the Park dq-reference equivalent models are implemented by DIgSILENT [5]. This is based on work by Bernd Rüdiger Oswald namely "Netzberechnung, Bd.2, Berechnung transients Vorgänge in Elektroenergieversorgungsnetzen" released in 1996 and "Berechnung von Drehstromnetzen: Berechnung stationärer und nichtstationärer Vorgänge mit Symmetrischen Komponenten und Raumzeigern" second edition released in 2013 as well as the IEEE's "Guide for Synchronous Generator Modelling Practices and Applications in Power System Stability Analyses" released in 2002. These equivalent models are specifically used for RMS and EMT simulations done in PowerFactory.

Figure 3.7 depicts the d-axis equivalent circuit for the standard synchronous model. Figure 3.8 and figure 3.9 represent the q-axis salient and cylindrical rotor equivalent circuits respectively.

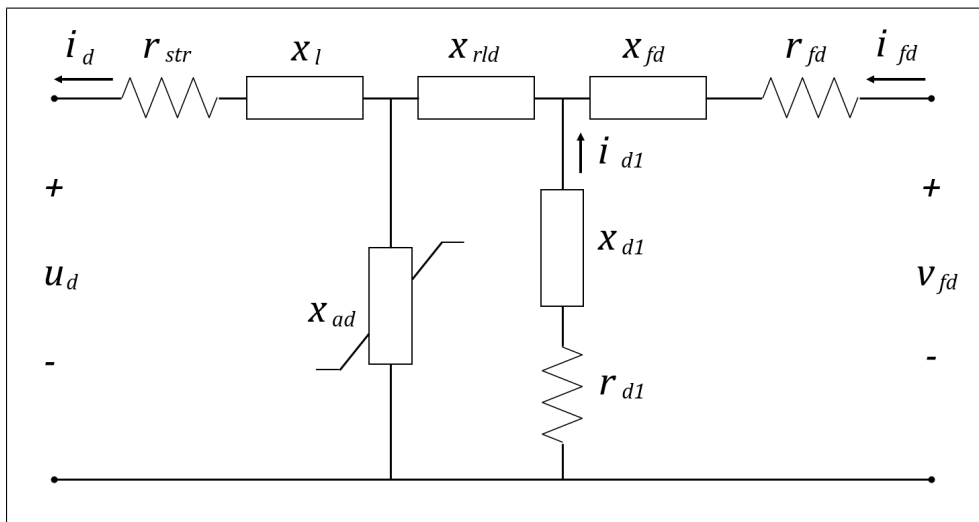


Figure 3.7: Standard model d-axis equivalent circuit. Adapted from [5].

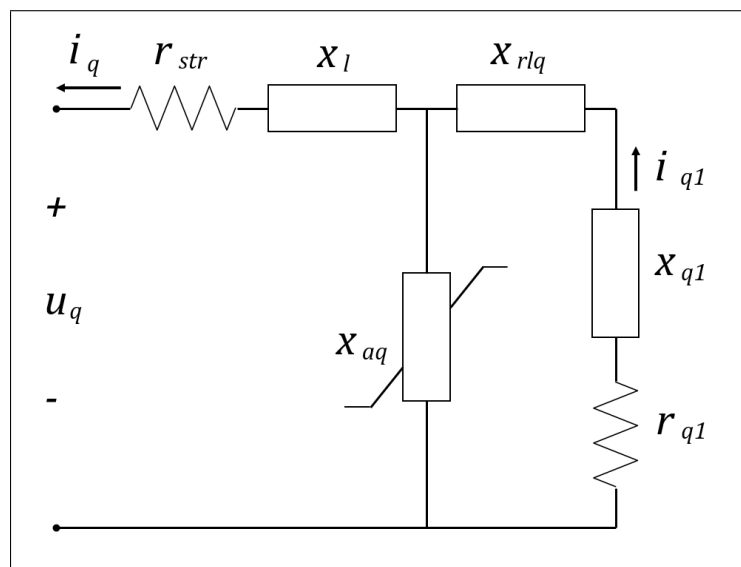


Figure 3.8: Standard model q-axis equivalent circuit for salient rotor. Adapted from [5].

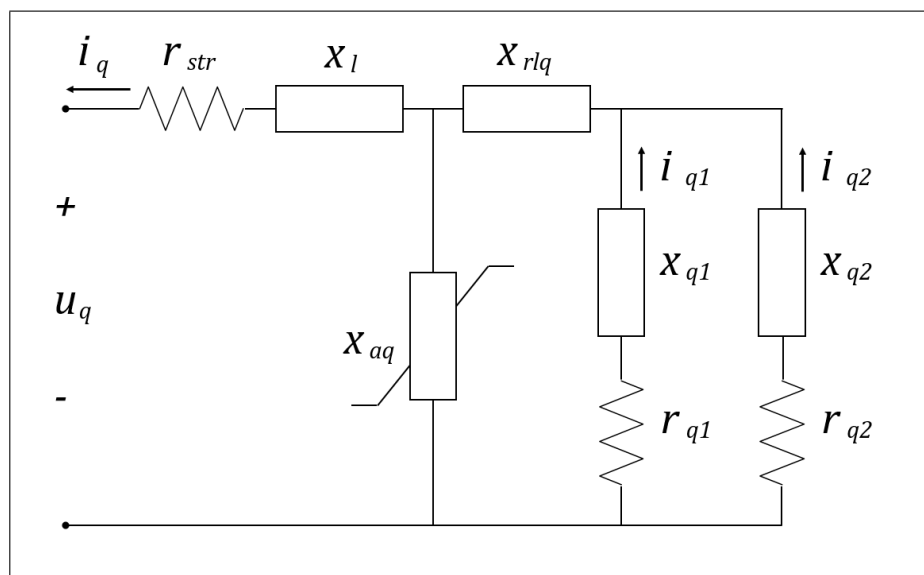


Figure 3.9: Standard model q-axis equivalent circuit for cylindrical rotor. Adapted from [5].

From the equivalent circuits in figure 3.7, 3.8 and 3.9, differential equations for a synchronous model can be derived. Differential equations 3.14 and 3.15 are used to describe the stator voltages.

$$u_d = u_d'' - r_{str} \times i_d + n \times x_q'' \times i_q \quad (3.14)$$

$$u_q = u_q'' - r_{str} \times i_q + n \times x_d'' \times i_d \quad (3.15)$$

With,

$$u_d'' = -n \times \psi_q^n \quad (3.16)$$

and

$$u_q'' = n \times \psi_d^n. \quad (3.17)$$

$r_{str}$  signifies stator resistance,  $x_d''$  and  $x_q''$  subtransient d- and q-axis reactance,  $\psi$  stator flux and finally  $i_d$  and  $i_q$  d- and q- axis rotor currents.

### 3.4.3 Solar array and inverter

Power produced by the PV installation is a fixed input parameter in the simulation. Irradiation changes are not needed.

A three-phase inverter converts the DC output of the PV installation to AC and is converted to the dq-reference frame to be compatible to the synchronous generator modelling.

### 3.4.4 Battery storage system

Ideally, the ESS of a microgrid should be able to operate in both current source and voltage forming modes. Its voltage forming operation is to provide a reference for other DERs and loads connected to the PCC if the synchronous generator is not operating. Most of the time, the ESS's operation time will be in current source mode as the microgrid will be operated grid-connected mostly. Its main contribution will be to support the EMS, by charging or discharging, as seen necessary by the control configuration.

A solid-state (non-rotating) generator modelling of the ESS was implemented in DIgSILENT. It has the ability to use different primary energy sources such as fuel cells, wind generators, reactive power compensators and storage devices [6].

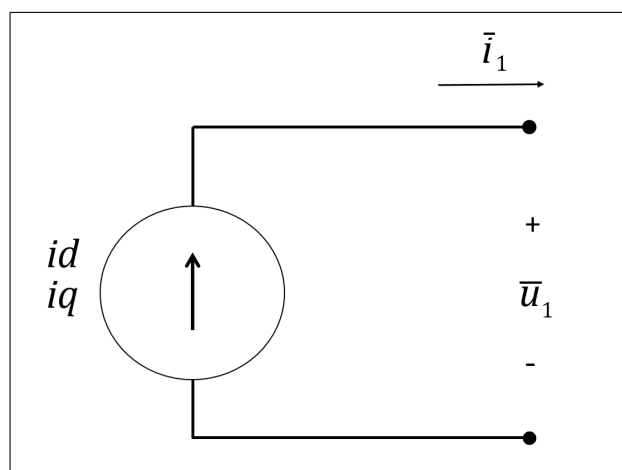


Figure 3.10: Solid-state generator model as current source. Adapted from [6].

Figure 3.10 depicts the model used when operating in current mode, making use of Park coordinates.

The positive sequence current  $\bar{i}_1$  can be calculated as:

$$\bar{i}_1 = (i_d \times \cos\theta - i_q \times \sin\theta) + j(i_d \times \sin\theta + i_q \times \cos\theta), \quad (3.18)$$

with  $i_d$  and  $i_q$  as direct and quadrature current references and  $\theta$  as the current reference angle.

$\cos\theta$  and  $\sin\theta$  can be calculated as:

$$\cos\theta = \frac{\text{Re}(u_1)}{|u_1|} \quad (3.19)$$

and

$$\sin\theta = \frac{\text{Im}(u_1)}{|u_1|}, \quad (3.20)$$

with  $u_1$  as positive sequence voltage.

To calculate negative sequence current  $\bar{i}_2$  the following formula is used:

$$\bar{i}_2 = (i_{d2} \times \cos\theta + i_{q2} \times \sin\theta) + j(i_{d2} \times \sin\theta - i_{q2} \times \cos\theta). \quad (3.21)$$

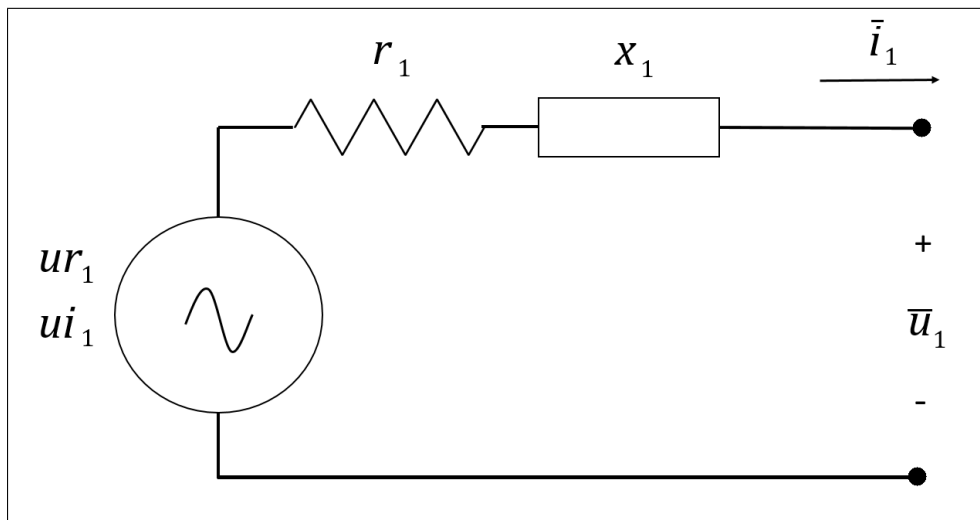


Figure 3.11: Solid-state generator model as voltage source. Adopted from [6].

Figure 3.11 depicts the transient model (to include dynamic operating conditions) of the static generator when used as a voltage source. Equation (3.22) defines the real part of the positive sequence voltage input  $u_{r1}$  and the imaginary part of the positive sequence voltage input  $u_{i1}$ . Field data needed in equations (3.22 - 3.26) are the nominal

apparent power rating  $S_n$ , series reactor copper losses  $P_{cu}$  and the series reactor short-circuit impedance  $z_{sc}$  in %.

$$u_{r1} + ju_{i1} = \bar{u}_1 + \frac{\underline{z}_1}{S_n \times \underline{i}_1} \quad (3.22)$$

$$z_1 = \frac{z_{sc}}{100} \quad (3.23)$$

$$r_1 = \frac{P_{cu}}{100 \times S_n} \quad (3.24)$$

$$x_1 = \sqrt{\sqrt{z_1} - \sqrt{r_1}} \quad (3.25)$$

$$r_1 + jx_1 \quad (3.26)$$

Note that if the reference voltage is below its minimum operating value during current-source mode the current output will be set to 0 and the ESS will only turn back on when the voltage is 5% higher than its minimum operation value. This set as an operational condition

To determine the negative real  $u_{r2}$  and imaginary  $u_{i2}$  voltage elements (3.27) is used:

$$u_{r2} + ju_{i2} = \bar{u}_2 + \bar{z}_2 \times \bar{i}_2. \quad (3.27)$$

### 3.4.5 Load model

Depending on desired simulation scenario balanced and unbalanced three-phase loads can be used. Figure 3.12 depicts the single-phase equivalent configuration of a load. Provision is made for non-linear and variable loading. [7].

Dynamic simulation can be realised from real field conditions. Using the compressor load profile obtained from field measurements (figure 4.10) different of ramp and step load events, shown in figure 3.13 were used to realise similar conditions in PowerFactory.

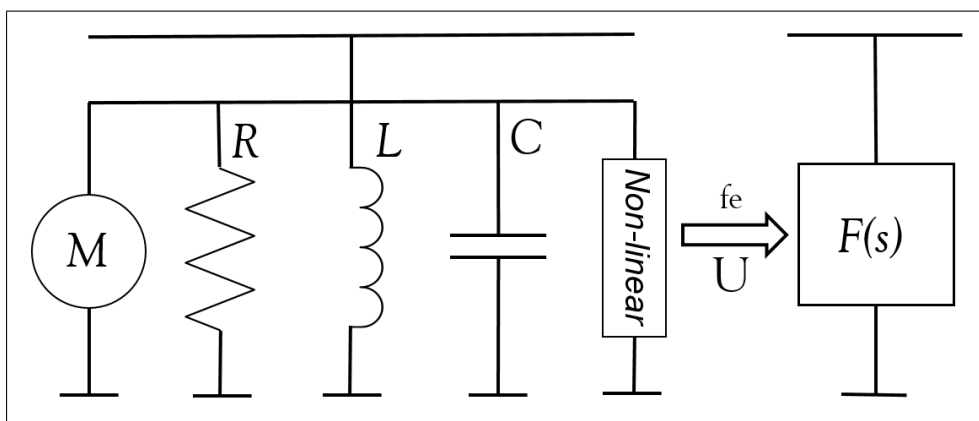


Figure 3.12: A single-phase equivalent model of microgrid load. Adapted from [7].

|                     | Name | Time        | Object                   | Out of Service       | Object modified | Object modified by |
|---------------------|------|-------------|--------------------------|----------------------|-----------------|--------------------|
| Switch Event_genset | 10.  | Gen_Incomer | <input type="checkbox"/> | 22-Aug-18 1:52:32 PM | Spy             |                    |
| Switch Event        | 15.  | LV_Load7    | <input type="checkbox"/> | 22-Aug-18 1:52:32 PM | Spy             |                    |
| Step Down           | 22.  | Load 7      | <input type="checkbox"/> | 22-Aug-18 1:52:32 PM | Spy             |                    |
| Load Event          | 24.  | Load 7      | <input type="checkbox"/> | 22-Aug-18 1:52:32 PM | Spy             |                    |
| Ramp down           | 29.  | Load 7      | <input type="checkbox"/> | 22-Aug-18 1:52:32 PM | Spy             |                    |
| Load Drop           | 31.  | LV_Load7    | <input type="checkbox"/> | 22-Aug-18 1:52:32 PM | Spy             |                    |
| Switch Event_Island | 33.  | LV_Incomer1 | <input type="checkbox"/> | 22-Aug-18 1:52:32 PM | Spy             |                    |
| Switch Event2       | 37.  | LV_Load8    | <input type="checkbox"/> | 22-Aug-18 1:52:32 PM | Spy             |                    |
| Step Down2          | 42.  | Load 8      | <input type="checkbox"/> | 22-Aug-18 1:52:32 PM | Spy             |                    |
| Load Event2         | 44.  | Load 8      | <input type="checkbox"/> | 22-Aug-18 1:52:32 PM | Spy             |                    |
| Ramp down2          | 49.  | Load 8      | <input type="checkbox"/> | 22-Aug-18 1:52:32 PM | Spy             |                    |
| Load Drop2          | 51.  | LV_Load8    | <input type="checkbox"/> | 22-Aug-18 1:52:32 PM | Spy             |                    |

Figure 3.13: Event list used to model load change

### 3.5 Microgrid control

Control of the microgrid was implemented using the Current-, Voltage- and Power Parameter slots (DIgSILENTS term for function blocks in DSL) as seen in figure 3.14. Other more complex methods of control were tested but did not correlate well with field data.

Voltage control is achieved by a first-order PID controller. Equation (3.28) shows the PID transfer function in the Laplace domain [50].  $K_p$  is the product constant,  $K_i$  integral constant and  $K_d$  the differential constant, which sets the computational weight for

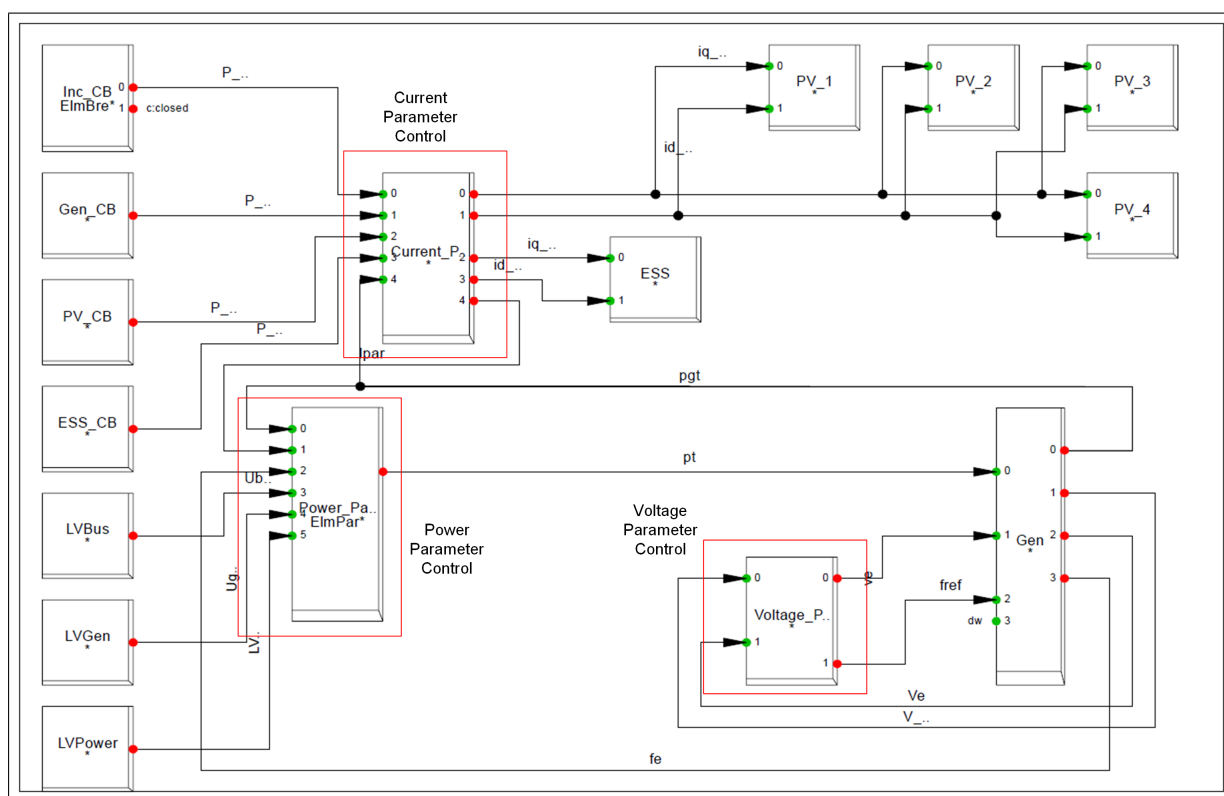


Figure 3.14: Microgrid control frame in DIgSILENT

control calculations. A delay function (which simulates the real communication delay in the practical system) is applied to the input signal. A set reference voltage value is used as input to the PID controller with the actual synchronous generator terminal voltage as a feedback signal.

A limiting function is used on the PID output to limit the exciter voltage to realistic operable values. When the ESS is operating in a voltage forming mode, the voltage parameter slot uses PID control to set reference values for positive and negative sequence voltages.

$$U(s) = (K_p + \frac{K_i}{s} + sK_d)E(s) \quad (3.28)$$

In the power control slot, a PI controller with a delay function is set the output power reference value for the generator. Note that a constant power value cannot be used as the LV network's power demand is dynamic. A power reference value for the generator is obtained by linear approximation using a lookup table. The lookup table com-

compares generator frequency to network frequency to determine the change in power needed to keep the network at stable operating levels.

Synchronisation to the utility's network makes use of a basic "IF" function. A change in power setpoint changes the generator frequency when loading is constant. Small but continuous changes in the power setting are used to keep the generator voltages synchronised to the network.

PID and PI controllers are tuned by means of the practical method discussed in [51].

The current control strategy is derived from the system operating mode. The type of grid-tied PV inverters used in this microgrid can only operate as current sources, whereas the ESS is planned to possess both voltage forming and current source functionality.

When the ESS operates in its current source mode the dq-reference frame described in section 3.4.1 provides active and reactive power according to microgrid objectives. The ESS in this microgrid did not have the ability to charge and discharge in supporting dynamic network events and only contribute to long term EMS objectives. The use of this system to support dynamic behaviour may be implemented in the future.

The system PV array and inverters can only operate as a current source. Power production at the PV installation is manually set assuming a fixed irradiance level during the period simulated.

Within this operating mode, the inverters produce all the power as allowed by the MPPT. When curtailed, it produces no power as adjustments in between is not allowed. Curtailment is needed when the microgrid is in islanded mode and the synchronous generator is operating at its minimum output limit. A logic flipflop function (that uses set and reset functions) simulates real-world response times of the inverters in question. This function is needed to prevent oscillation at the inverters.

## 3.6 Verification

A number of assumptions were made during the modelling of a microgrid. To assess the extent by which these simplifications of the real-world model affect the usefulness of the DIgSILENT model, it is verified in this section against other known modelling studies of microgrids.

Final evaluation of the DIgSILENT model is done in the next chapter by validating the simulation model against field data. This is done to ensure that the modelling approach is useful for the main requirements of this study, namely to develop a simulation tool for microgrid response predictions. The simulations are not done on individual component level to simulate the operation of for example the Insulated Gate Bipolar Transistors (IGBT)'s used in the inverters, it was done from an EMS perspective (the smallest components are the DERs and loads as a whole).

The user of the DIgSILENT model will plan real-world operating scenario's and by having transient conditions included, the operation of the microgrid as a whole will be realistically predicted before the adjustments in operational conditions are implemented. To verify if the results obtained from this simulation model is indeed realistic reference microgrid cases were used.

Internationally, microgrids are a relatively new and fast developing field with knowledge continuously forthcoming. Three peer reviewed publications on how other microgrid developers have approached the engineering and design of a microgrid are used in this dissertation as a baseline in verification of the DIgSILENT model developed.

Response profiles were created through the use of these peer reviewed literature sources. These profiles denote the expected response during certain dynamic events. The sources are:

- Practical measurements taken at China's Henan College of Finance and Taxation's microgrid [1]. This microgrid has a similar LV topology with differences

being a larger peak load (600 kVA) and larger PV capacity (380 kW), but with a similar ESS (200 kW with a 200 kW/h capacity).

- Lab scale microgrid emulation in [13]. The lab model consists out of two DG units connected to the PCC through VSIs, and a static RLC load.
- Two microgrid simulation models in [13, 52]. MATLAB/Simulink was used for the model in [13] and PSCAD for the model in [52].

The source profiles were compared and verified to share the same response trends. Dynamic phenomena that were accounted in the above reference baseline cases, are:

1. Synchronisation between generator and utility network when transitioning from an islanded to a grid-connected mode.
2. Islanding of microgrid.
3. Voltage magnitude and frequency control of LV network during dynamic loading conditions (during islanded operation).

The goal of this comparison is simply to verify that the DIgSILENT model produces similar dynamic responses to that of peer reviewed study cases.

### 3.6.1 Synchronisation

When synchronizing a generator to the utility, both voltage magnitude and phase difference between the two sources are important even when the frequency difference between the voltage sources are perfectly similar. In order to align the phase angles between similar phases, speed of the synchronous generator in the grid requires careful adjustment to either decrease or increase the angular difference, and when zero, to maintain it until the voltage magnitude is similar before the synchronisation breaker can be closed. Some fluctuation in instantaneous voltage and frequency thereafter is

expected until a steady-state operating condition is reached. Figure 3.15 depicts an example of such synchronisation during laboratory controlled conditions of a microgrid, similar to the microgrid developed during the research reported in this dissertation, being synchronised to the grid.

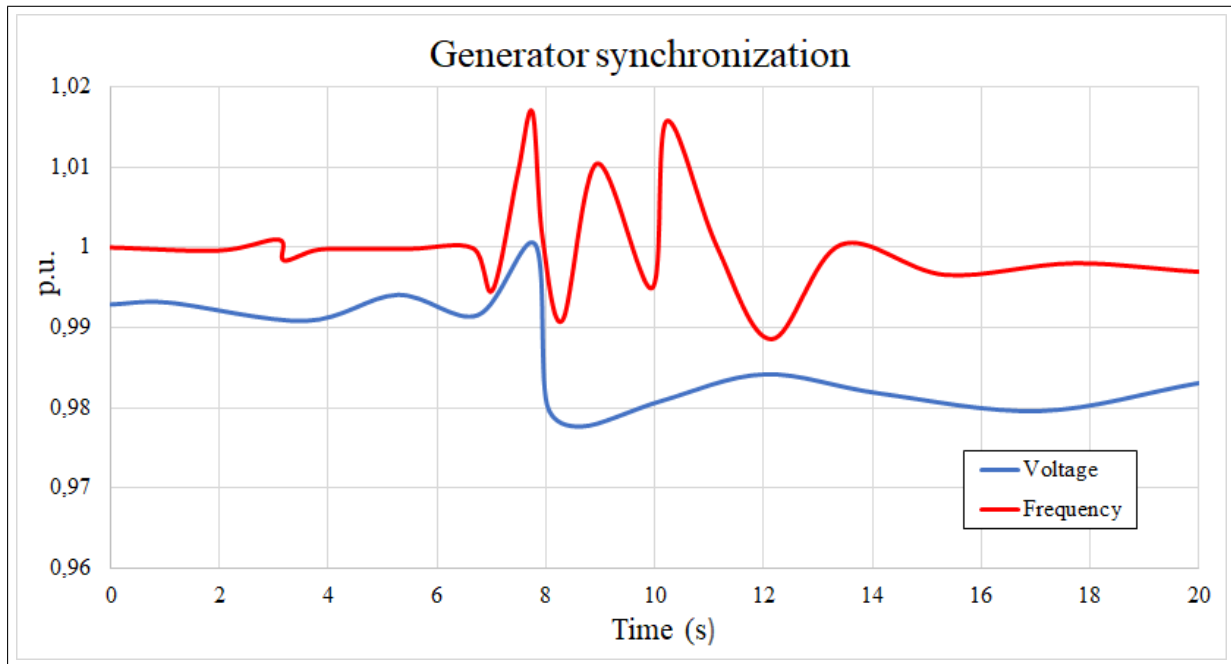


Figure 3.15: Study case generator synchronisation voltage and frequency profile. Adapted from [13].

Similar synchronisation events were created in the DIgSILENT model. The results are respectively shown in figure 3.16.

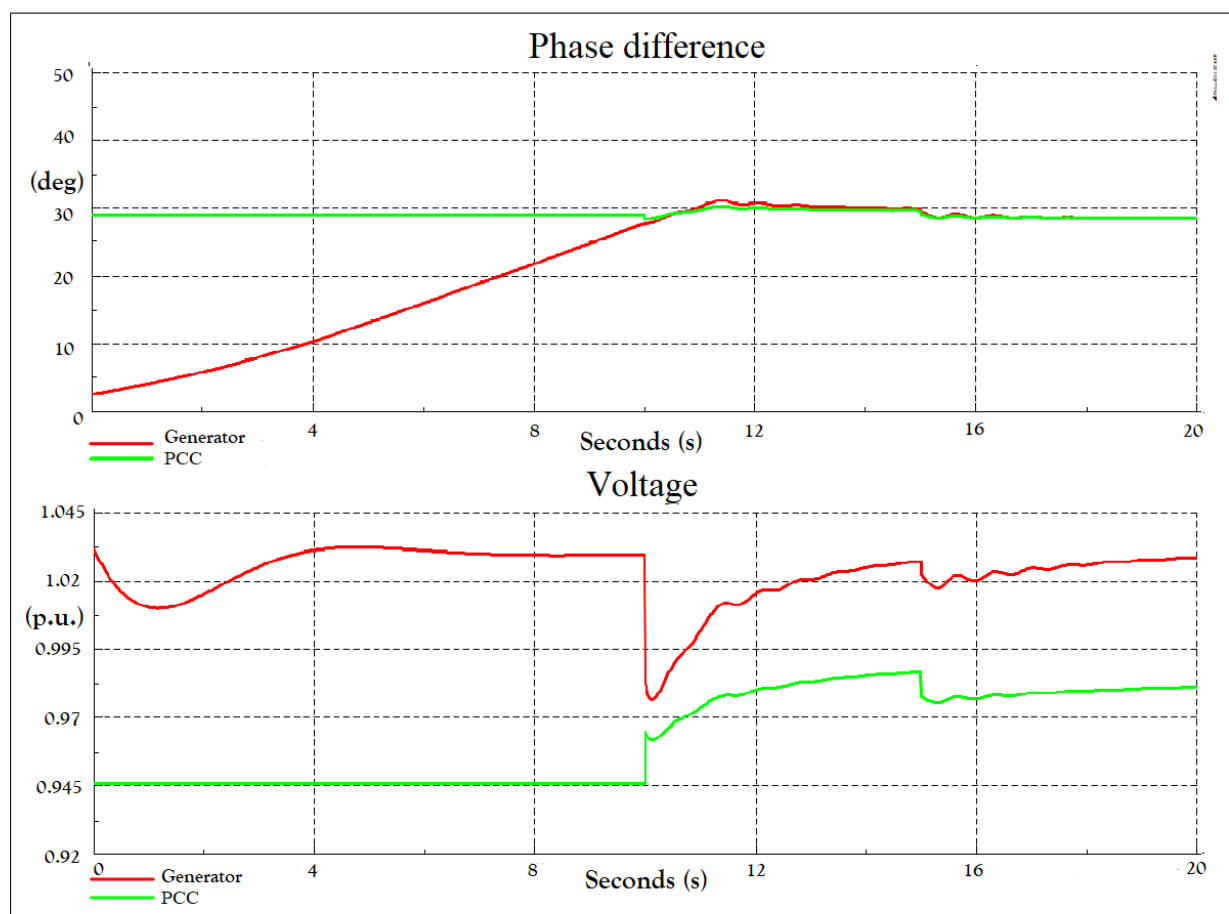


Figure 3.16: Simulation generator and PCC voltage magnitude and phase at synchronisation.

The synchronous generator has the ability to linearly and in a controlled fashion to adjust the angular difference between the grid voltage reference and the voltage waveform generated by the synchronous generator. When synchronised, the oscillation is the result of the speed control on the primary mover that has to perfectly match the frequency of the generator with that of the grid.

Frequency at the PCC is shown in figure 3.17. The oscillatory behaviour of frequency at the generator (there is an impedance between the point where the grid voltage is measured and where the generator voltage is measured) is the result of the speed-controller (governor) of the generator attempting to perfectly match the speed (frequency) of the generator to the grid. Due to the mechanical inertia in the machine-generator system,

it takes some time to stabilise.

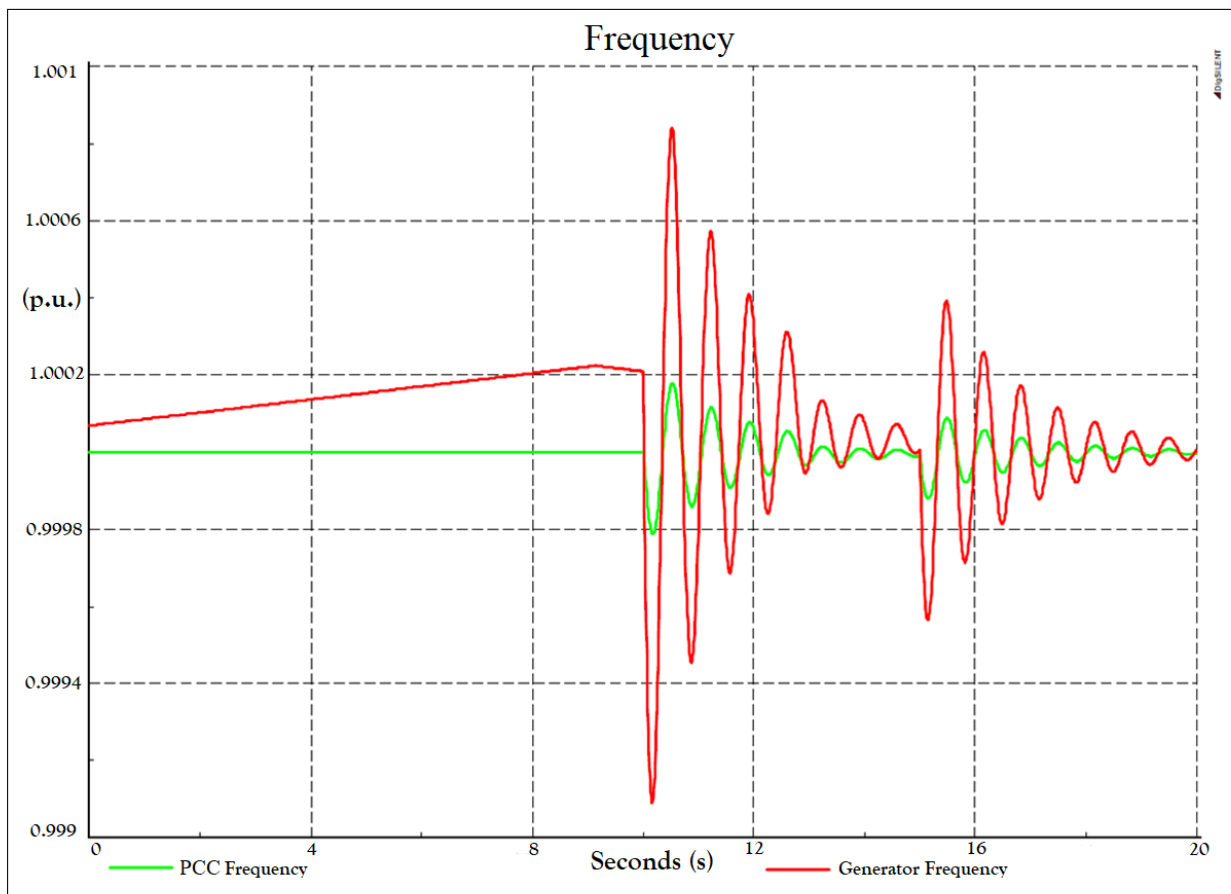


Figure 3.17: Simulation generator and PCC frequency at synchronisation.

The transient condition in the generator did not cause more than a  $\pm 0.05$  Hz difference.

The difference in frequency oscillation between figure 3.15 and 3.17 is due to difference in governor settings

### 3.6.2 Islanding

The utility's network has an abundance of inertia and high fault levels due to its low impedance. When the microgrid operates in grid-connected mode the utility dominates it's frequency due to these characteristics, and the microgrid follows (adjusts to)

the frequency changes in the grid.

Voltage magnitude is also dictated by the grid due to the low fault level. The different energy sources in the microgrid has to adjust their voltages to match the grid voltage.

The profile in figure 3.18 is used as a reference case of a standard (normal) event when transition from grid-connected to islanded mode.

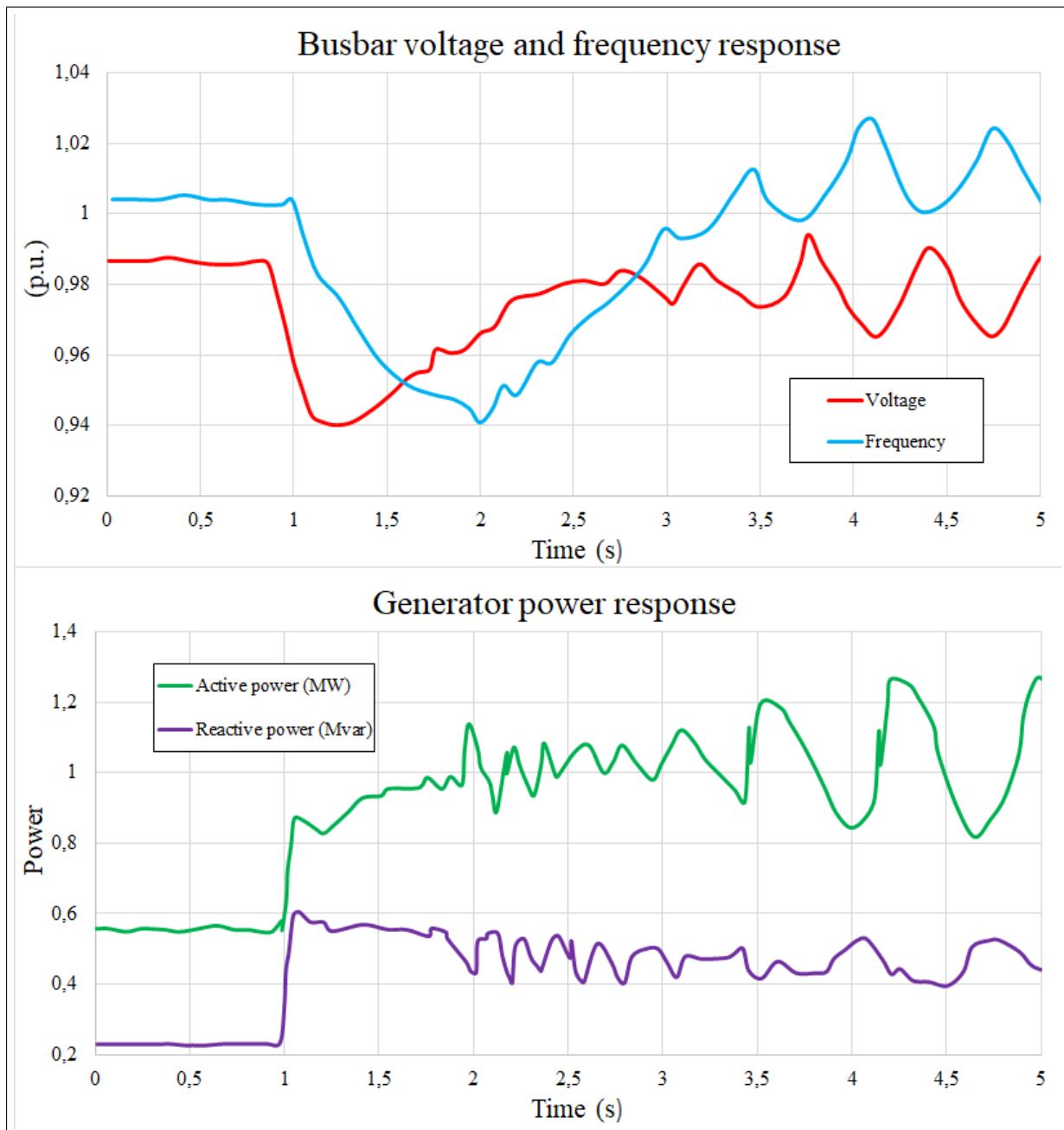


Figure 3.18: Study case islanding verification profile. Adapted from [52].

Islanding occurs at 1 s in figure 3.18. A drop in voltage and frequency (microgrid has lost the grid connection) is followed by compensating with active and reactive power in order to match loading with demand in maintaining frequency. Fast compensation is needed to prevent unnecessary load shedding or interruptions. This may lead to

overcompensation that can cause overshoot followed by an oscillation period before reaching steady-state operation once again.

Under islanded conditions, controlling the DERs to obtain stable operation is more complex. A transient condition when the microgrid transitions from being grid-connected to islanded, is simulated in figure 3.19.

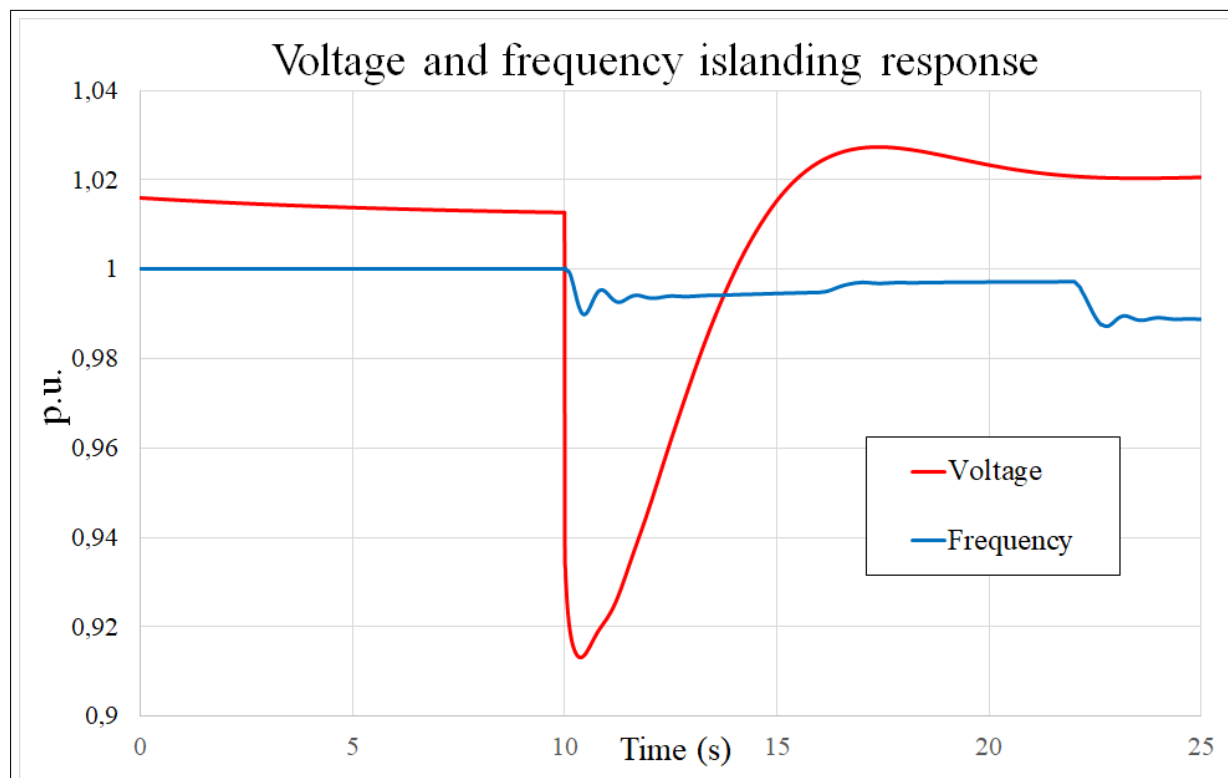


Figure 3.19: Simulation voltage and frequency of PCC at islanding

In figure 3.19 the moment of islanding can be seen at 10 s. Initially, the system voltage and frequency drops and then oscillates slightly until stabilised at new operating levels. When comparing figure 3.19 with the reference profile in figure 3.18 it is evident that both responses follow a similar dynamic trend.

From the switching profile in figure 3.18 the response is that both the voltage and system frequency drops below its previous operating level. This is due to the sudden burden placed on the DER units in the microgrid.

The step change in voltage realised when transitioning from grid-connection to an islanded mode in figure 3.19 is the result of the field controllers having to adjust the reactive power production of the synchronous generator to match the requirements of the loads in the microgrid. This compensation characteristically overshoots, causing a short oscillation period before settling at steady-state levels.

In the response obtained from the simulation model, the same drop in voltage and frequency can be seen, with voltage sagging more but oscillating less. The voltage drop in the simulation is more due to the generator not producing the same ratio (less) of reactive power when transitioning from grid-connected to islanding mode and oscillates less due to a better tuned AVR controller. Both figures 3.18 and 3.19 shows similar trends that serves as a qualitative assessment of the simulation model and considered as verified for the goals of the microgrid.

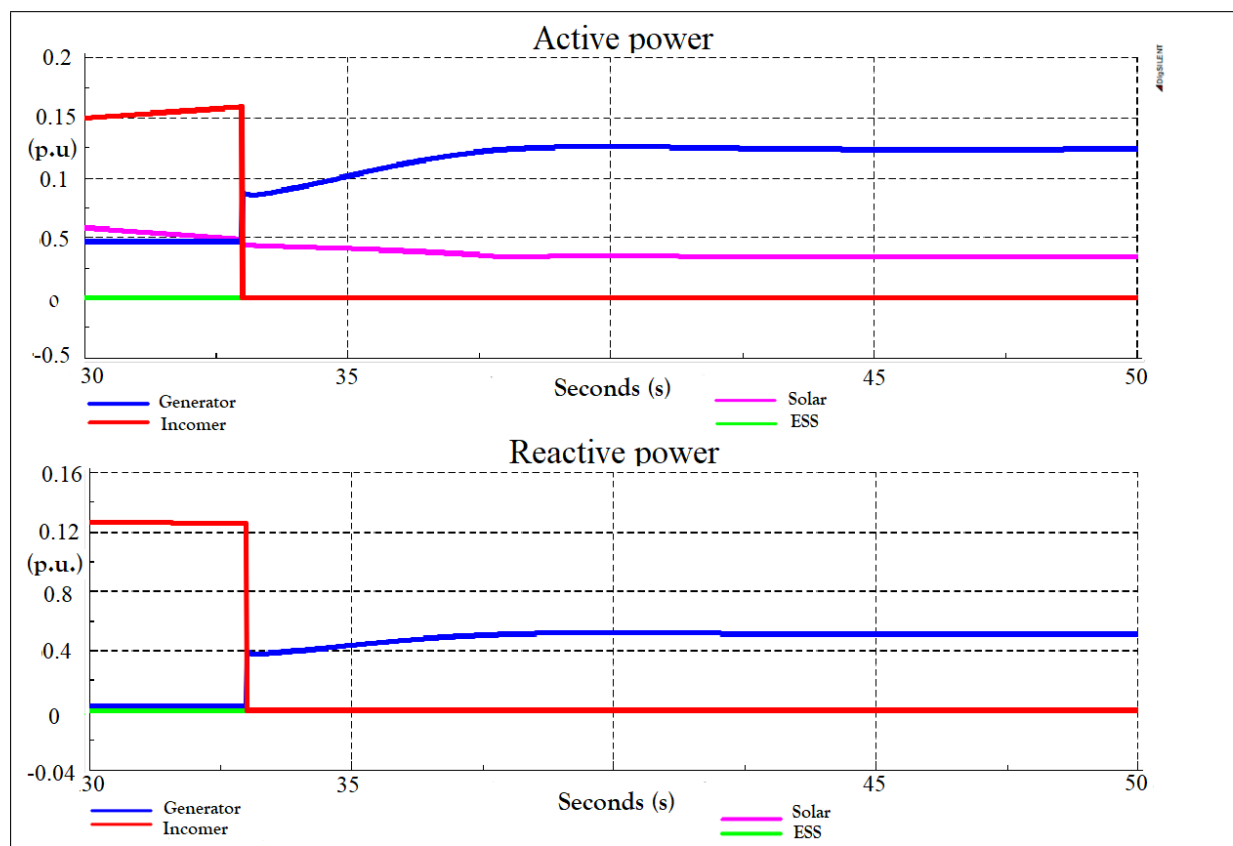


Figure 3.20: Energy contribution by different energy resources within the microgrid

Figure 3.20 depicts the power contribution by each DER when grid-connected and when islanded (after 33 s). The moment of islanding is clearly visible at 33 s when the synchronous generator's active power production drastically rises. This sudden increase in power (active and reactive) production is expected as the microgrid DERs now have to supply the microgrid load without grid-support. Active power production has a direct correlation to diesel consumption of the synchronous generator and is why it is kept to the minimum before islanding. Similar responses can be seen in both figure 3.20 and 3.18.

### 3.6.3 Dynamic loading condition

A dynamic load condition is typically caused when the microgrid load increases or decreases significantly within a short amount of time. In islanded mode the effects of a dynamic loading event are larger than when grid connected due to the larger inertia and lower impedance that the utility's grid provides.

When experiencing a load step (increase) the same type of trend seen when islanding is expected. This is due to the microgrid DERs needing time to react to the sudden shortage of active and reactive power to keep the system voltage and frequency stable.

The opposite is true when experiencing a sudden load drop (decrease), as seen in the study case profile in figure 3.21.

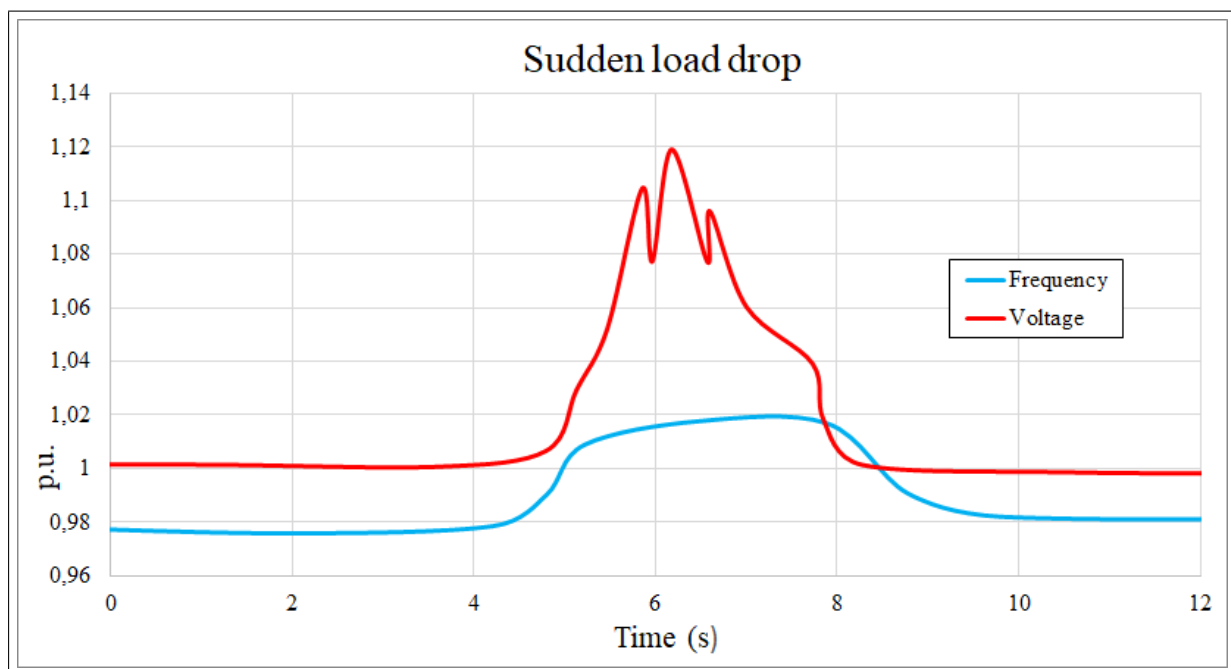


Figure 3.21: Study case voltage and frequency response during a sudden load drop. Adapted from [13].

When the load decreases at 4.2 s the microgrid is taxed with an excess of active and reactive power. This causes a voltage and frequency swell until the DERs connected to the PCC can compensate.

Figure 3.22 shows the simulation results when the DiGSILENT model was exposed to the same type of loading event.

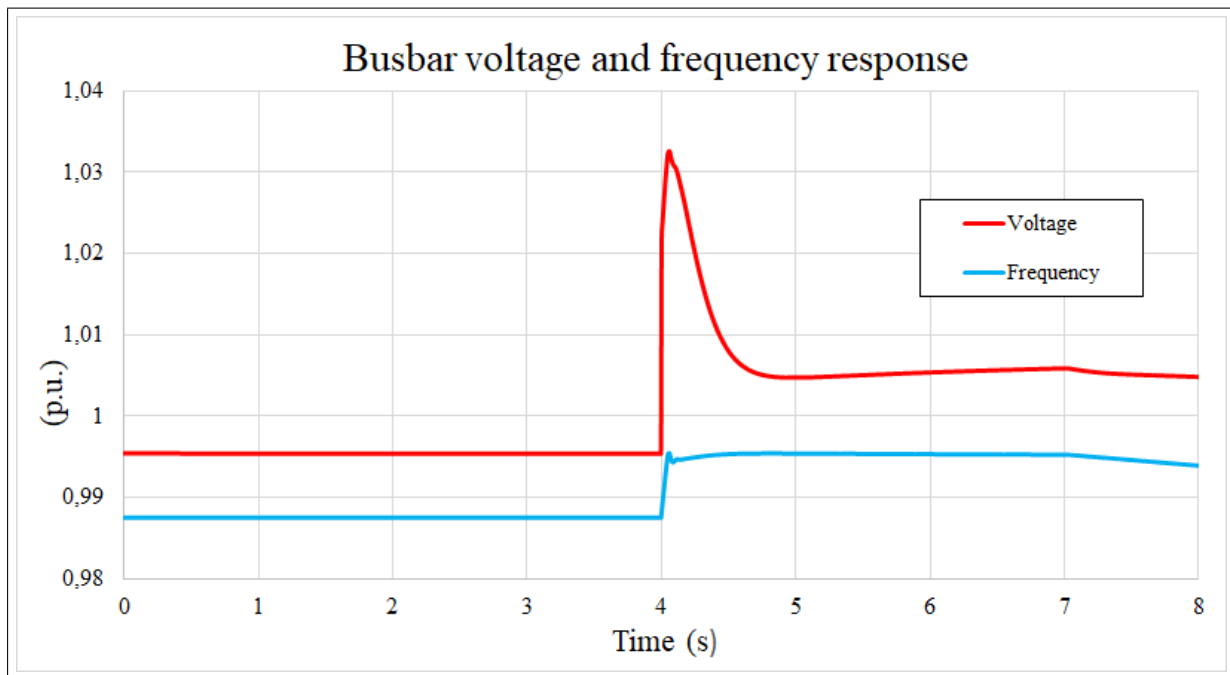


Figure 3.22: Simulation voltage and frequency response during a sudden load drop.

The difference in voltage and frequency swell magnitude and duration may be caused by a difference in the amount that the load decreased, capability of the DERs connected to the PCC and/or the control setting differences of those DERs. Another difference where the frequency for figure 3.22 settles at a higher steady state value than before the loading event is due to the system operating at its maximum output before the load decreasing. This load decrease is significant enough for the DERs to operate closer to the microgrid voltage and frequency set points.

Both figures 3.21 and 3.22 have similar response trends verifying the DIgSILENT model response to dynamic loading conditions.

Using peer reviewed literature sources to create dynamic trend profiles adds a method of model verification that allows the model developer to better understand deviations in microgrid transient behavior. It also ensures that the model used in the verification process of matching these trend profiles provides accurate predictions of a microgrid's response to dynamic events introduced into the system. The model verification done in

section 3.6 provided satisfactory results ensuring that the model is ready to be adapted to represent the industrial microgrid used in this research study.

### 3.7 Conclusion

Useful modelling of a microgrid has to correctly predict both the steady state and dynamic behaviour. As demonstrated proper research should be done not only on how the practical system operates but how the mathematical models meant to represent this practical system, within the project's most applicable simulation environment, can be used to converge to an expected outcome. Using DlgSILENT PowerFactory, sufficient complexity was retained as results correlated well to the real world study case used as verification in section 3.6.

Successfully verified, the model retains enough flexibility to be adapted to any microgrid of similar topology. The control methods used are robust and easily adjustable. When combined with the accurate modelling methods of the different DERs, introducing changes to the system as part of development is an easy process which will produce results equivalent to that expected in literature.

Next, using field data this microgrid model will be validated as a final test for being useful in designing and predicting the performance of microgrids. This will allow the evaluation of control strategies within a microgrid to optimize performance.

# Chapter 4

## Validation by means of field data

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*In this chapter operational data is obtained analyzed and discussed. Section 4.2 focuses on how the data was measured and used. Detailed analysis of trends and events is presented in section 4.3. Field data obtained is implemented in the DIgSILENT model in section 4.4. Model validation through field data comparison is discussed in section 4.5*

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### 4.1 Introduction

During the field tests, the reference microgrid was not operating at full capacity. Valuable system understanding was gained, regardless, by collecting data under a number of controlled conditions.

Performance of the various DERs and their power quality contribution could be included in the field data and also serves as a reference for improving future control strategies.

Field data is analysed and then used to improve and validate the DIgSILENT model.

## 4.2 Field data acquisition

Practical measurements were done on the 8th of June 2018 at the reference LV industrial microgrid. Power quality recorders recorded data by means of the Class A measurement requirements of edition 3, IEC 61000-4-30 at the primary incomer from the utility, the diesel generator, PV installation and the ESS.

Figure 4.1 depicts the metering points and figure 4.2 is a photo of the physical installation. Appendix B discusses the measurement procedures followed. Each instrument was GPS time stamped to ensure that all recordings were done synchronously.

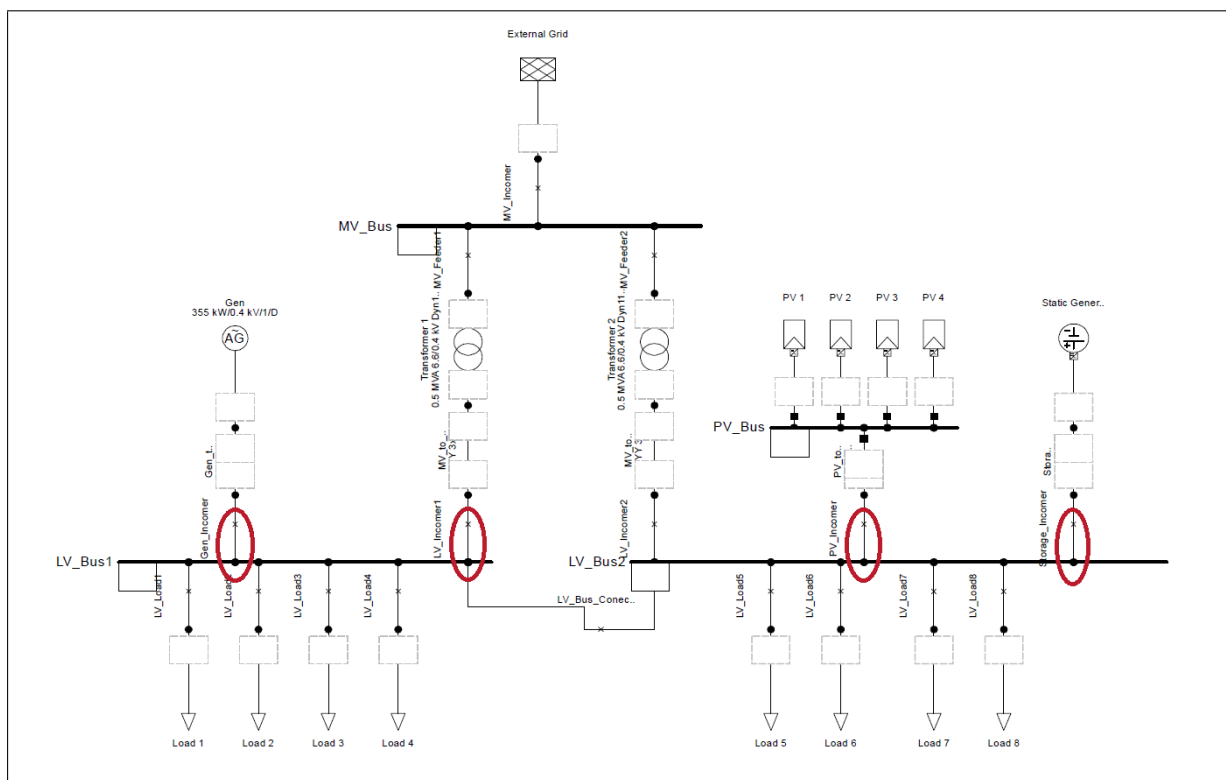


Figure 4.1: Schematic displaying points where meters were installed

As discussed in appendix B various changes were introduced into the system throughout the afternoon test period. As the test period overlapped with a Friday afternoon shift, the production plant was not operating at full capacity. However, there was a



Figure 4.2: Installation of a Vecto II and Impedo Duo metering instruments

sufficient load change present and thus useful data could be captured.

Data retained included all the different IEC 61000-4-30 measurement intervals [53]:

- Waveform data - During an event, waveform data was retained at a resolution of 1000 samples per fundamental frequency cycle. As the initial sample rate of the instruments in use is 500 kHz, it could be down-sampled to perfectly fit 1000 samples per fundamental frequency cycle even when not exactly 20 ms at 50 Hz.
- Frequency content - Up to 63<sup>rd</sup> harmonic order.
- 3s and 10 min data - Obtained by IEC 61000-4-30 aggregation of 200 ms block data.

## 4.3 Data analysis

Data were analysed for power quality performance in the LV microgrid and dynamic response at the various DER's. Data was not collected for compliance assessment to the technical minimum standards (NRS 048 part 2-2015), the goal was to assess the instantaneous PQ performance during the different configuration states of the microgrid, that includes steady-state operation and transient conditions revealing dynamic behaviour. PQ analysis was thus merely used as a method to understand dynamic behavior for use in the model developed.

### 4.3.1 Voltage regulation and unbalance

Voltage magnitude regulation was analyzed using IEC 61000-4-30 200 ms block data. The NRS 048 part 2-2015 requires that LV voltage regulation stay below nominal voltage +10 % and above nominal voltage -10 % for 95 % of the time and above nominal voltage -15 % for 99 % of the time [54]. The voltage stayed well within these limits on the LV bus, calculated as a minimum of 207 V (230-10%) and maximum of 253 V (230+10%) at a 230 V nominal phase-voltage.

Figure 4.3 depicts RMS voltages during the microgrid transition from grid-connected to islanded mode. A 2.5% - 3% increase in magnitude results from the diesel generator having a higher set point than the grid voltage during that time. This higher set point helps to mitigate voltage sag conditions when large loads are energized from the generator supply. Having a higher fault impedance than the distribution grid, a higher voltage drop is expected when the same load is energized from the islanded micro-grid compared to the grid-connected condition.

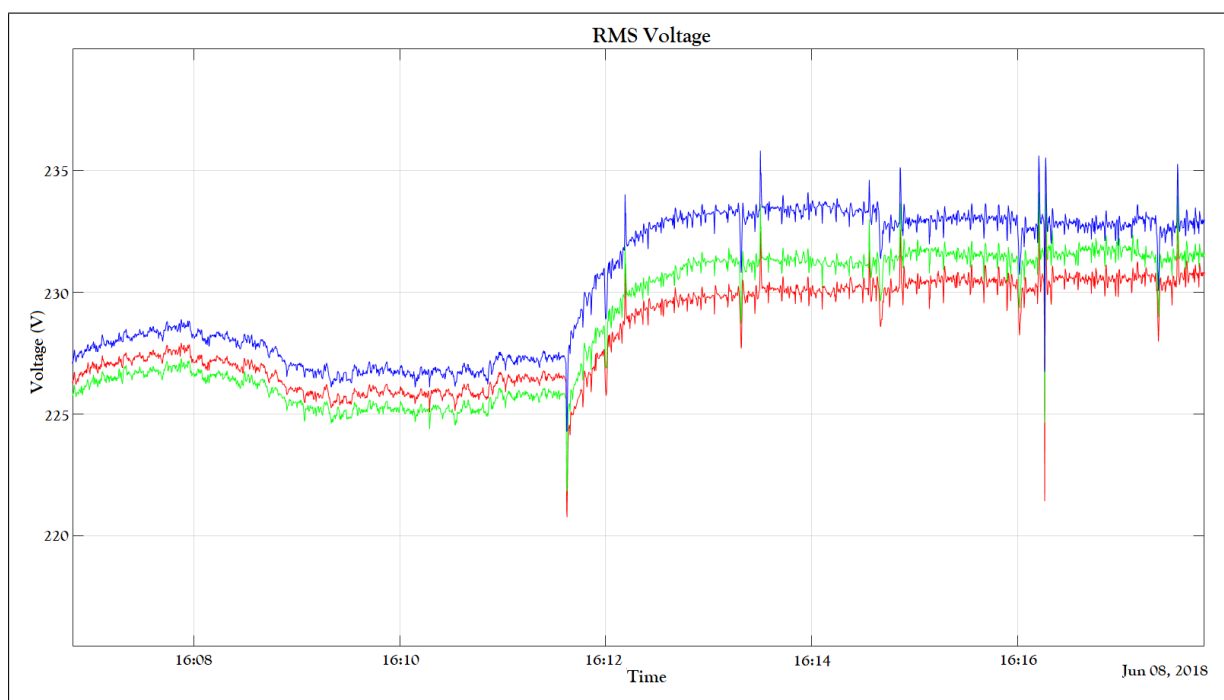


Figure 4.3: Voltage magnitude - Grid connected to islanded operation

Frequency regulation has a high affinity with that of voltage regulation, as the voltage-forming source is responsible for a nominal frequency reference, being the diesel generator in the islanded case. The NRS 048 stipulates maximum deviation from nominal frequency as 2% when grid-connected and 2.5% when islanded, this is  $\pm 1$  Hz and  $\pm 1.5$  Hz respectively in a 50 Hz network [54]. Figure 4.4 illustrates the frequency control as the network transitions from grid connected to islanded and back again. The network frequency is less stable in islanded mode, varying between 50.8 Hz and 49.3 Hz (excluding outliers), but within the limit values.

Variation in frequency during the islanded condition illustrates the importance of sufficient inertia in an AC power system. In this micro-grid, the diesel generator acts as both the voltage- and frequency reference. Voltage control relies on how well the implemented technology controls the field current. Frequency relies on the inertia set by the mass of the rotor, the speed of the rotor and the technology doing the speed control.

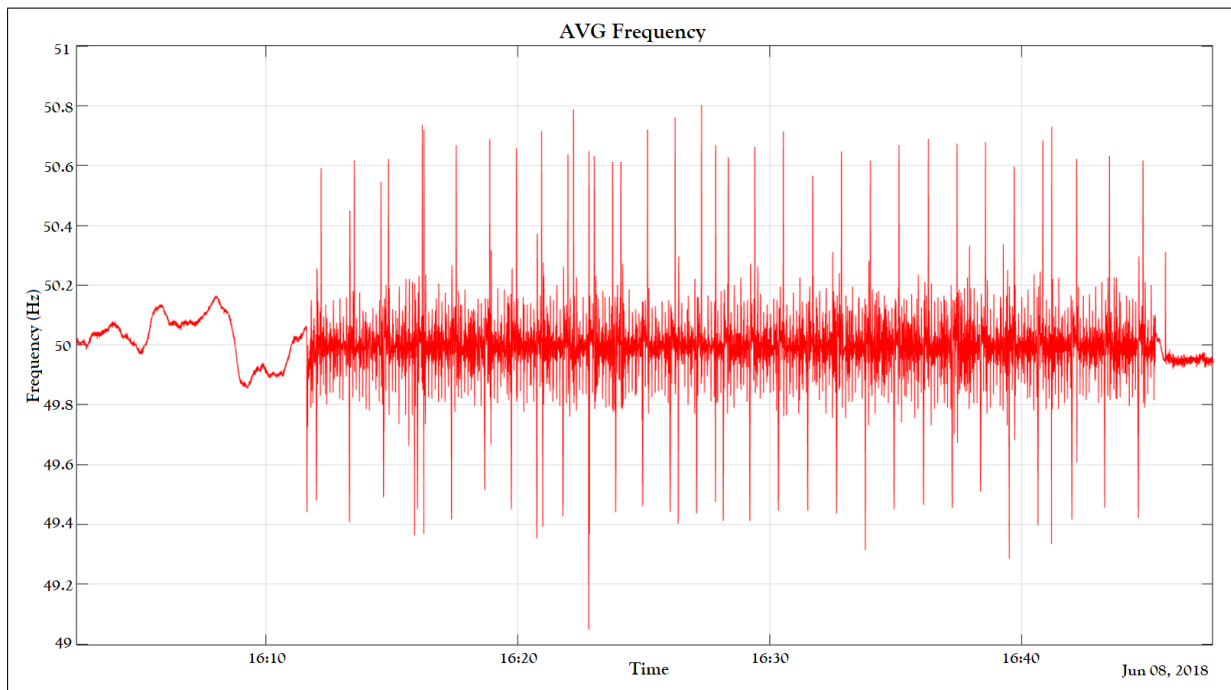


Figure 4.4: LV bus frequency - Grid connected to islanded operation

Voltage unbalance within the system as the different DERs switch in and out was analyzed next. In accordance with the NRS 048, the total unbalance value should be below 2% and can be calculated as,

$$V_{UB} = \frac{V_2}{V_1}, \quad (4.1)$$

with  $V_1$  and  $V_2$  the magnitude of the positive and negative sequence voltage phasors in the fundamental frequency, respectively.

In accordance with the National Electrical Manufacturers Association (NEMA) MG 1 standard motors can operate below 1 % unbalance without being degraded and should not operate above 5 % voltage unbalance.

Figure 4.5 depicts the microgrid when transitioning to islanded mode. It roughly doubled but is still well within the NRS 048 part 2-2015 compatibility requirement of being less than 2%. Data was not recorded for the minimum period of 7 days and is why the 95% requirement based on 10-min values was not assessed.

Voltage unbalance is higher due to the higher system impedance. The unbalance in load currents cause an unbalanced voltage drop between the supply impedances in each phase. Even with these phase impedances perfectly balanced, an unbalanced voltage results. With an increase in supply (fault) impedance when islanded compared to when grid-connected, the increase in voltage drop across the supply impedances commensurate with an increase in voltage unbalance.

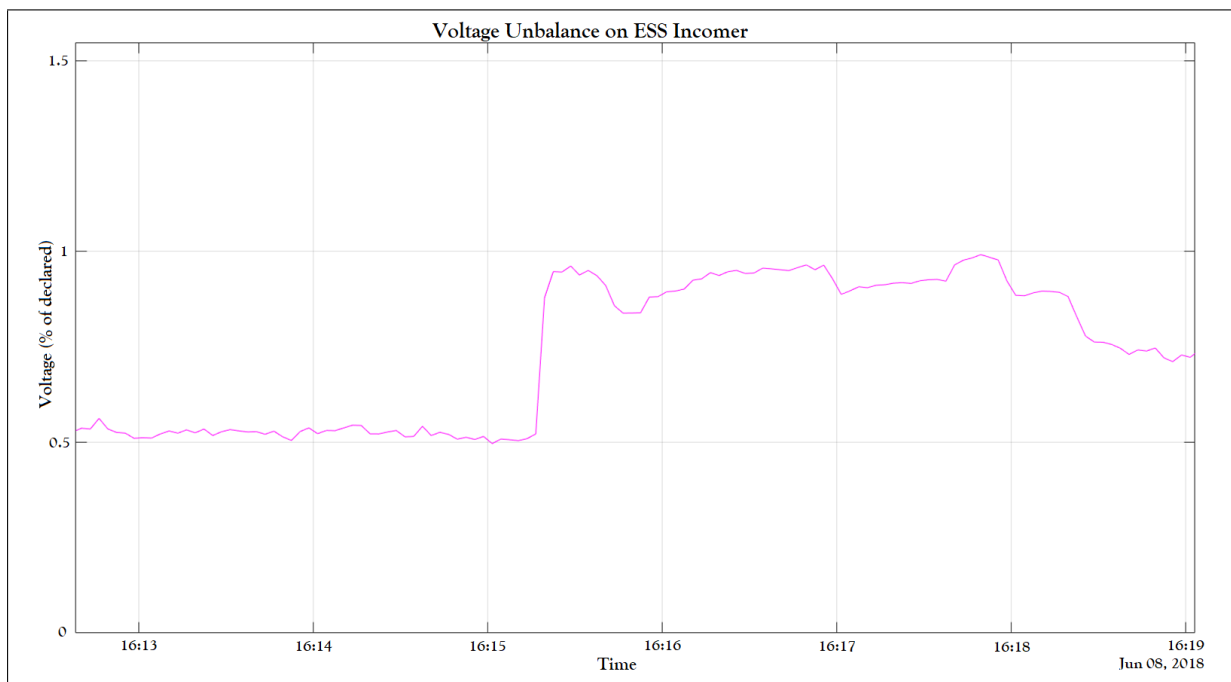


Figure 4.5: Highest level of unbalance measured

Unbalance transients exist at the moment of DER connection and disconnection (unbalance drops to 0 %) from the network at their various connection points. Figure 4.6 illustrates such a transient. These unbalance values are instantaneous and can be ignored as they do not have a significant effect on the network.

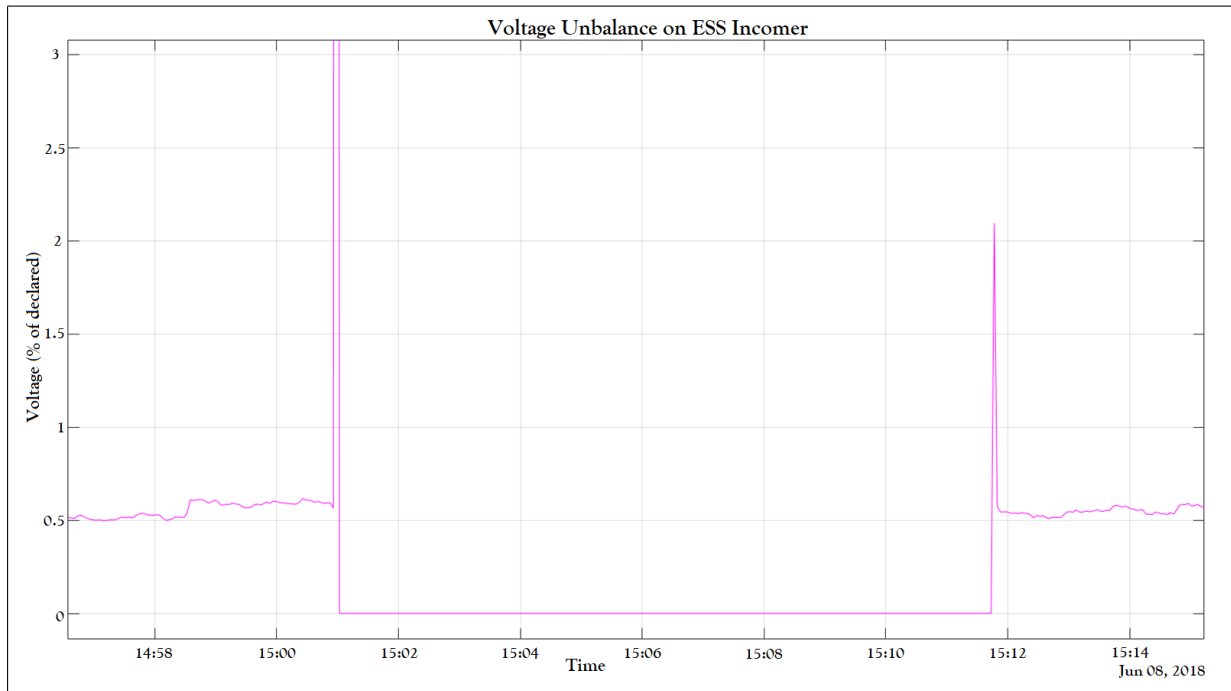


Figure 4.6: Voltage unbalance transient with ESS disconnecting at 15:01 and reconnecting 10 minutes later

### 4.3.2 Harmonics

Voltage Total Harmonic Distortion (THD) calculated per phase as,

$$V_{aTHD} = \frac{\sqrt{\sum_{i \neq 0,1}^N V_{ai}^2}}{V_{a1}}, \quad (4.2)$$

with  $V_{a1}$  the fundamental frequency voltage phasor magnitude in phase a and  $V_{ai}$  the harmonic frequency phasor magnitude of harmonic i in phase a.

The frequency of harmonics rises with 50 Hz per order as 50 Hz is the base frequency of the network. The 3rd harmonic, for example, will thus be at 150 Hz.

Compatibility is stated by the NRS 048 part 2-2015 as voltage THD to remain below 8% for 95% of the time in networks operated at and below 33 kV.

The trend for voltage THD per phase during the different test configurations is shown in figure 4.7.

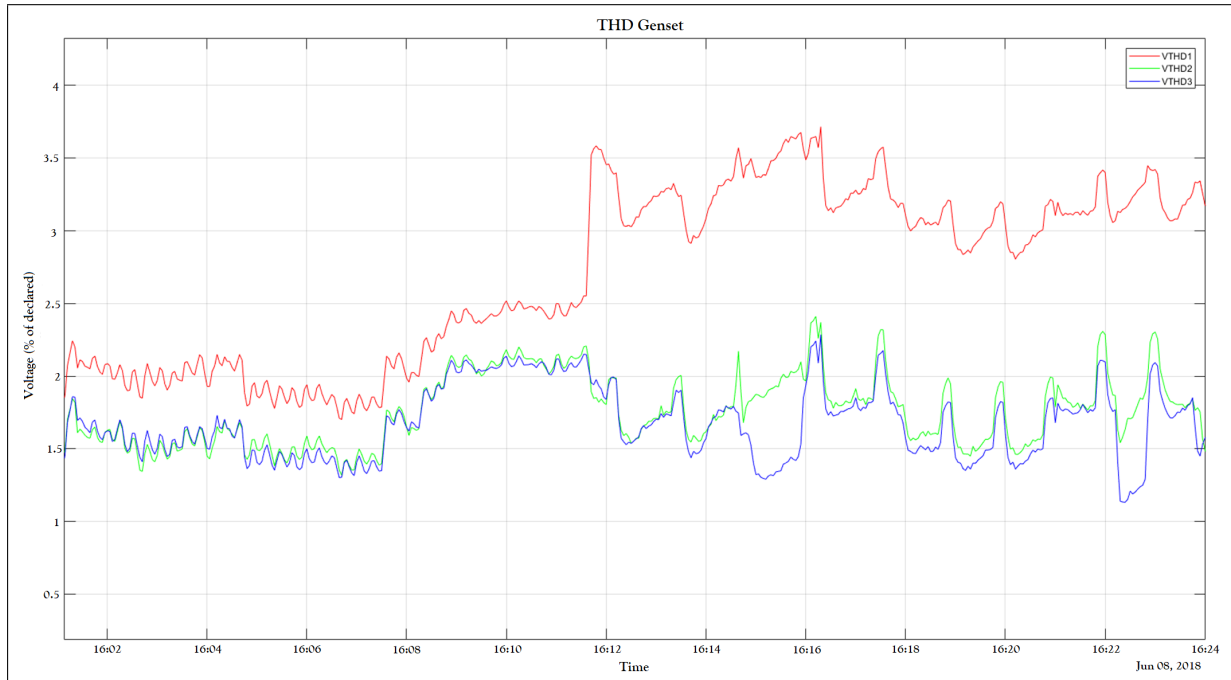


Figure 4.7: Voltage THD during islanding - Generator incomer

Voltage THD in the red phase is significantly different as single-phase distorting loads exist.

Part of the analysis was to record and review 10 minute individual harmonic values and an instance of these recordings are shown in figure 4.8. None of the individual values reviewed deemed further investigation.

All voltage harmonics remained well within the NRS 048 part 2-2015 requirements on compatibility for individual voltage harmonics.

Harmonic current emission produced by the diesel generator, PV plant and battery storage during islanded conditions are compared in figure 4.9 by means of synchronized recordings. During islanded conditions, due to the higher supply impedances, voltage harmonics resulting will be higher in magnitude compared to the grid-connected

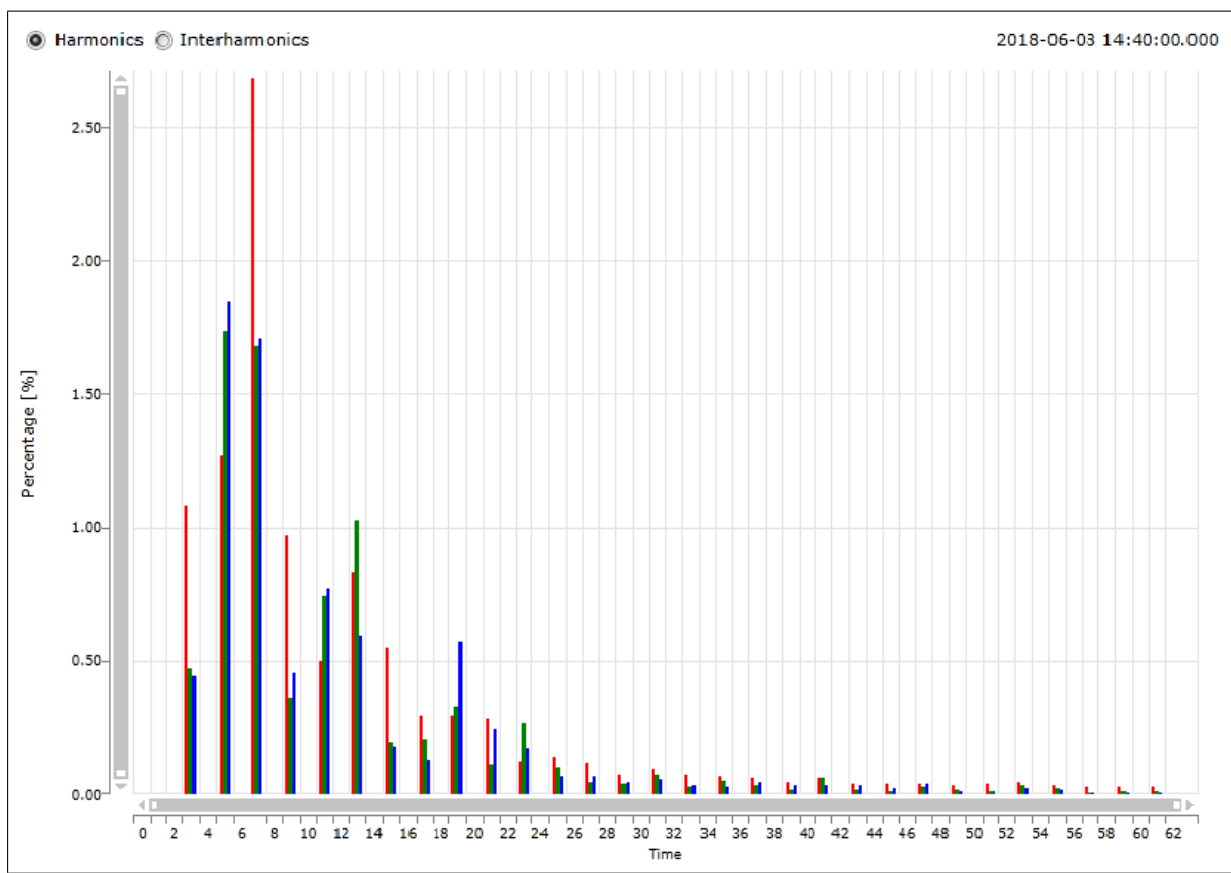


Figure 4.8: Individual harmonic orders measured - LV bus in grid-connected mode condition.

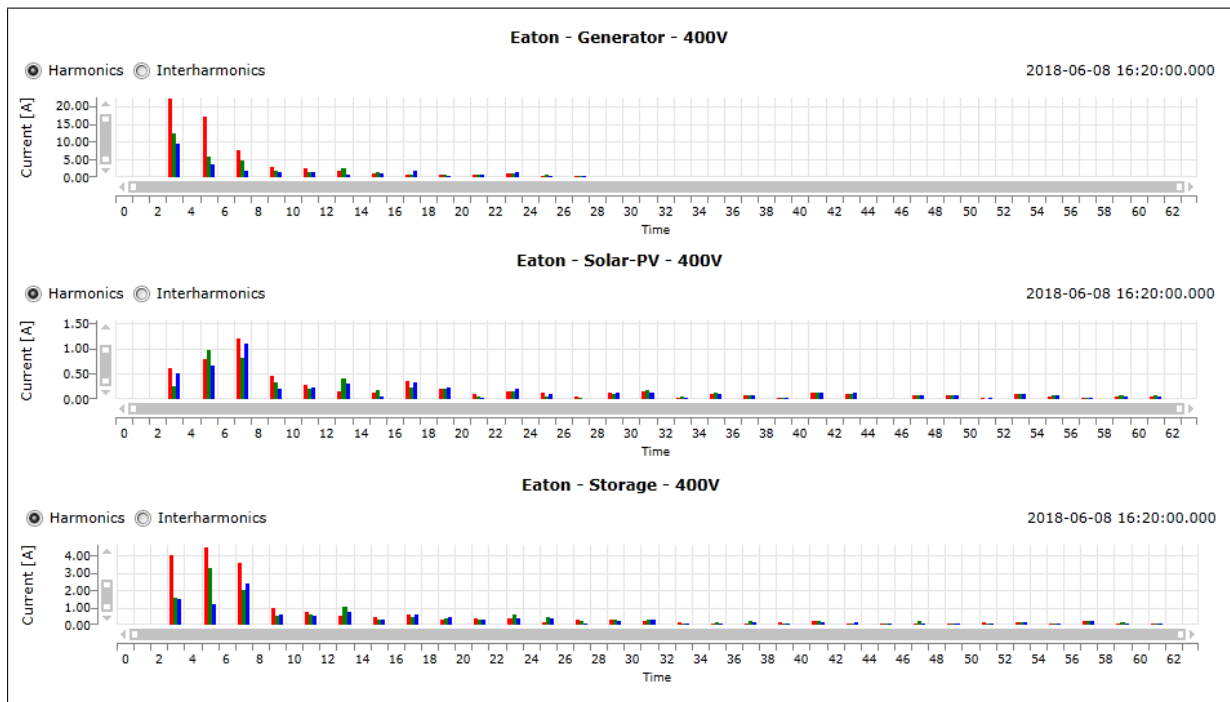


Figure 4.9: Individual harmonic orders measured

- Third harmonic current emission at the diesel generator is the highest with almost no harmonic emission above the 7th harmonic order.
- The unbalanced emission at the battery storage could not be explained as it expected that a three-phase grid-connected inverter should inject balanced harmonic currents.
- Harmonic emission from the PV inverter is the best balanced of the 3 energy resources.
- Different nonlinear single-phase loads exist and could explain why the harmonic current injection is not symmetrical between phases.

### 4.3.3 Energy analysis

Simultaneous active and reactive power measurements were taken at each energy resource during the grid-connected and islanded mode of operation as shown in figure 4.10. Total active and reactive power was measured at the grid incoming connection, the generator, the battery storage facility and the PV plant.

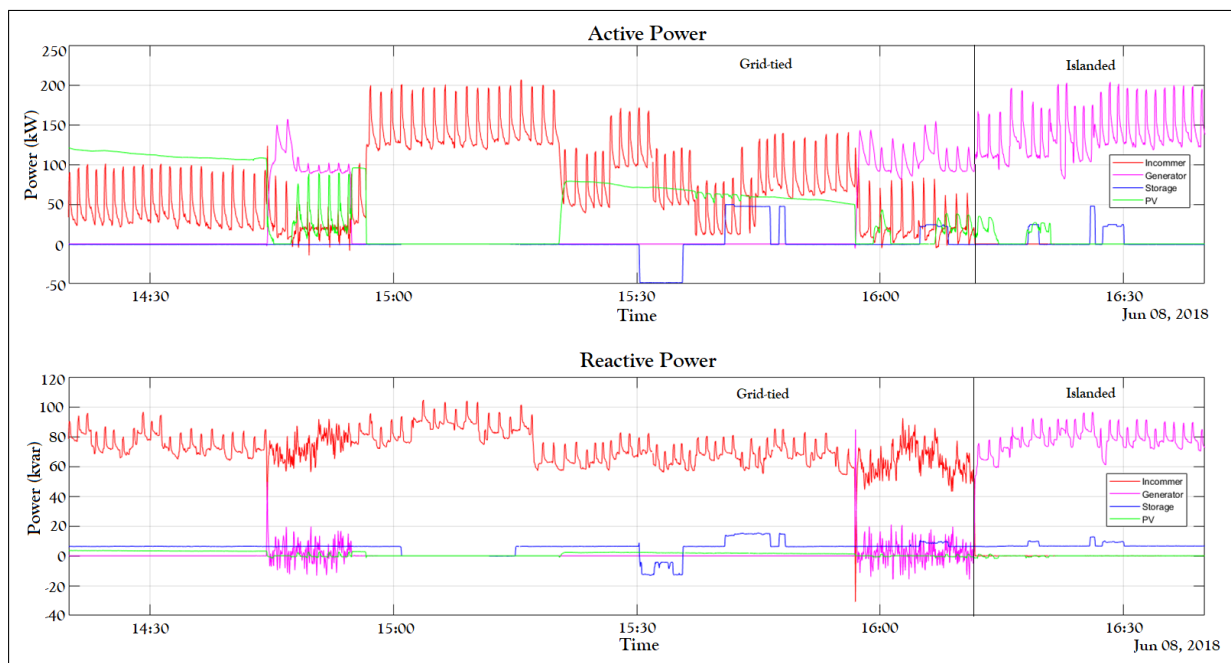


Figure 4.10: Active and reactive power contribution by individual DERs

Figure 4.11 depicts the energy consumption at the production facility of the factory against the RMS voltages.

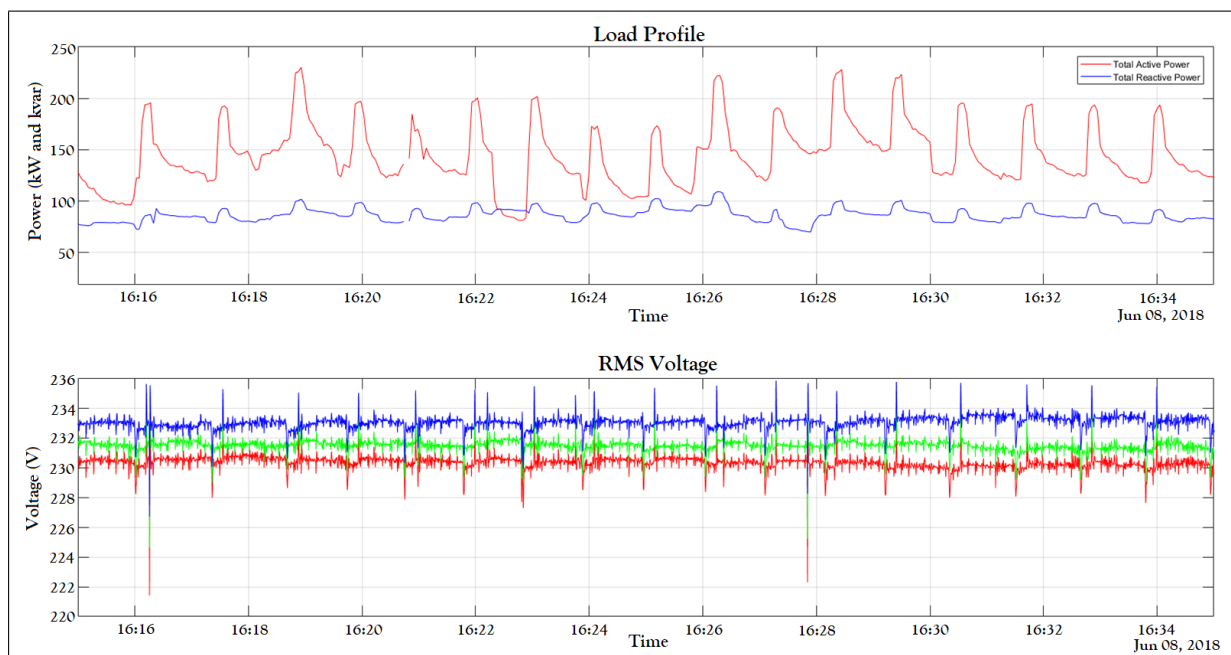


Figure 4.11: Individual harmonic orders measured - PV incomer

The compressor is responsible for the 80 kW step load increase resulting in minimal changes in the bus voltage even during islanded mode (when it is most susceptible to change).

#### 4.3.4 Voltage waveform events

Switching events were used to induce dynamic voltage events as shown in figure 4.12.

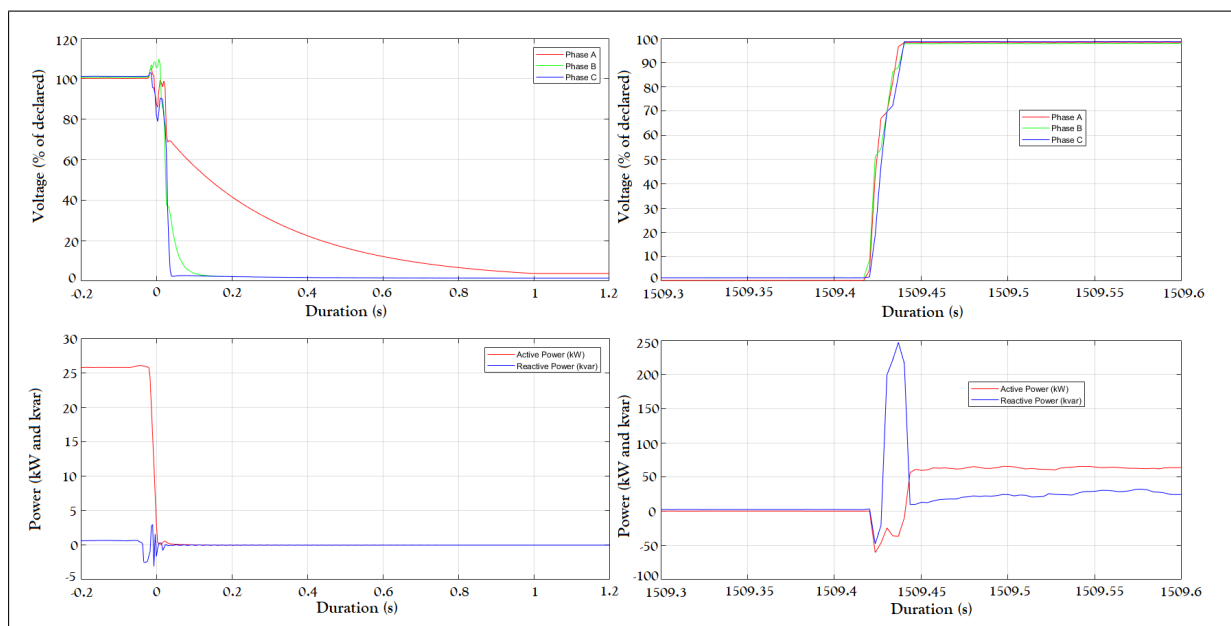


Figure 4.12: Sustained interruption - Measured at PV plant side of incomer

The sustained interruption of the PV plant was a manual disconnection done to monitor the network response with a loss of energy source.

Significant current changes were then induced as shown in figure 4.13. Controlled discharge of 50 kW was done by the battery storage system.

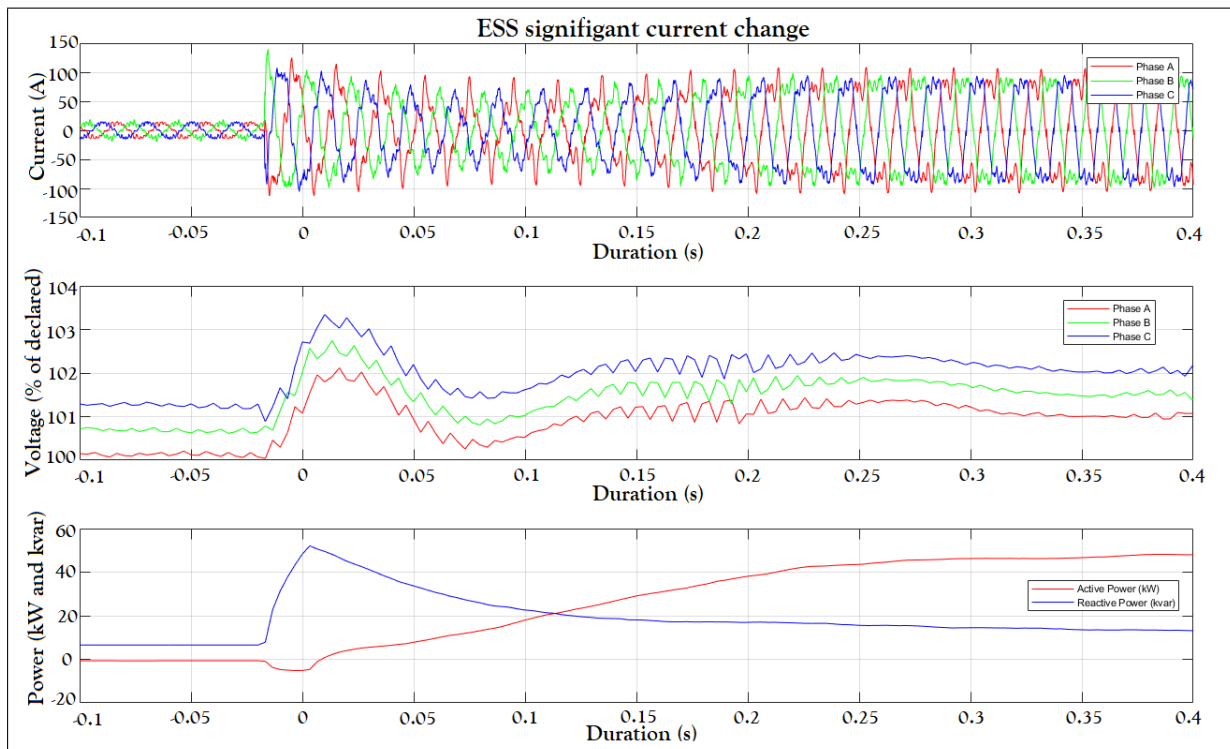


Figure 4.13: Significant current change event at the battery storage facility

- During the discharge of the battery facility, voltage is increased by 2% in the shared LV bus.
- Reactive power injection is initially high as the battery systems starts its discharge (which causes a voltage increase), and starts to stabilize a moment later as active power injection is steadily increased.
- Current injected is significantly distorted.

## 4.4 Use of data in model

Field data is used to validate and adapted the software model to increase accuracy. Secondly, field data is used to evaluate how the PV plant, battery storage facility and

the diesel generator control voltage and frequency during steady-state and dynamic conditions.

From the energy analysis a representative transient load and generation profile was implemented within the PowerFactory model. Using control set points close to those implemented in the field, provided results that mimicked field data, which is used to test system improvements within the simulation environment.

## **4.5 Model validation**

Validation of the simulation is done by comparing simulation results to field data. Comparable operation scenarios were identified with representative examples of the DER operation within the microgrid. Factors of interest include how active and reactive power production/absorption affect voltage and current control at the diesel generator, PV plant and battery storage.

Different time periods were used as the different resources react differently.

### **4.5.1 Islanded operation**

Under islanded condition, all external influence on the micro-grid operation is eliminated.

The onset of islanding provides a valuable transient event needed for model validation. DER configuration within the model was set to be the same as that of the test facility during the islanding process.

Voltage response when the generator transitions from a supportive (grid connected) to a voltage forming source (islanded) is shown in figure 4.14 by means of RMS voltage profiles. Field data and simulated data from the PowerFactory model is plotted on the same graph over a 30 second period, starting 9 seconds before islanding occurs.

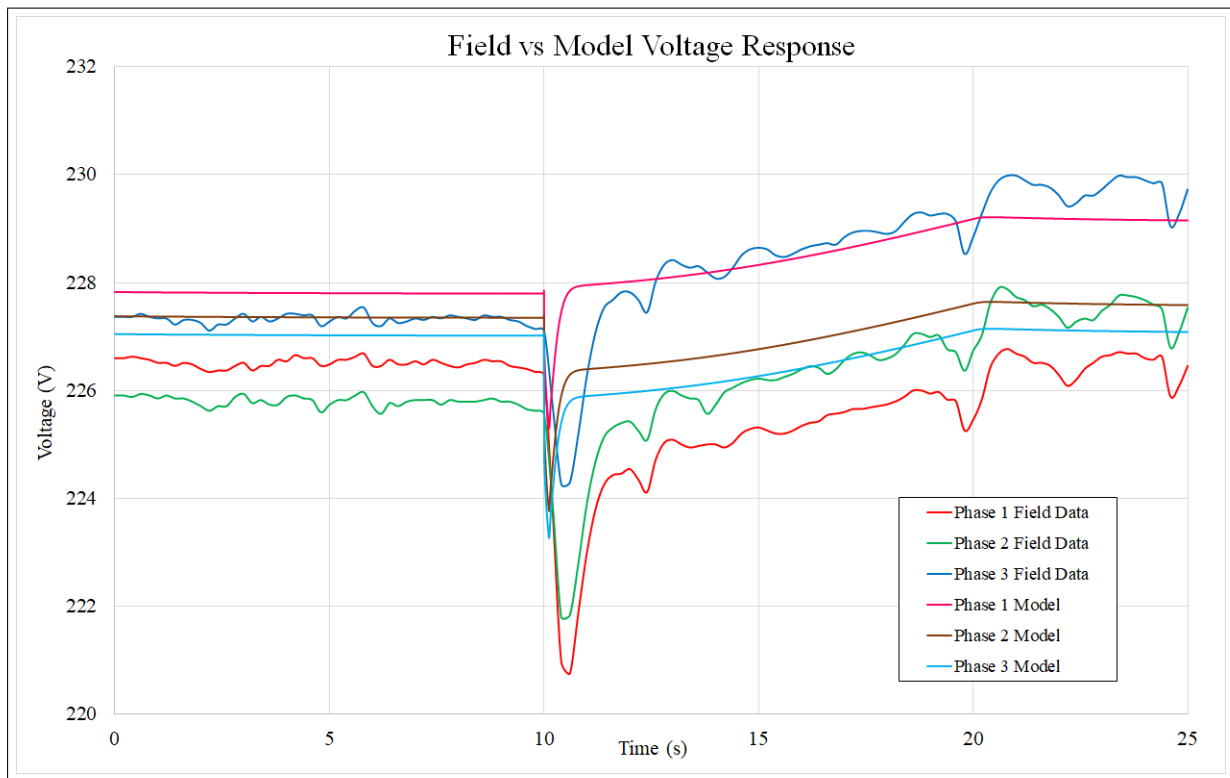


Figure 4.14: Voltage response when transitioning to islanded mode

The voltage sag condition predicted by the simulation model is slightly shallower and RMS voltage profiles overall much smoother. This can be attributed to ideal conditions that have to be used in the simulation model as exact modelling of all physical phenomena is not possible.

Voltage unbalance is compared in figure 4.15. During grid-connected conditions, voltage unbalance is higher than when islanded and well-predicted by the PowerFactory model. Field data validated the simulation model performance.

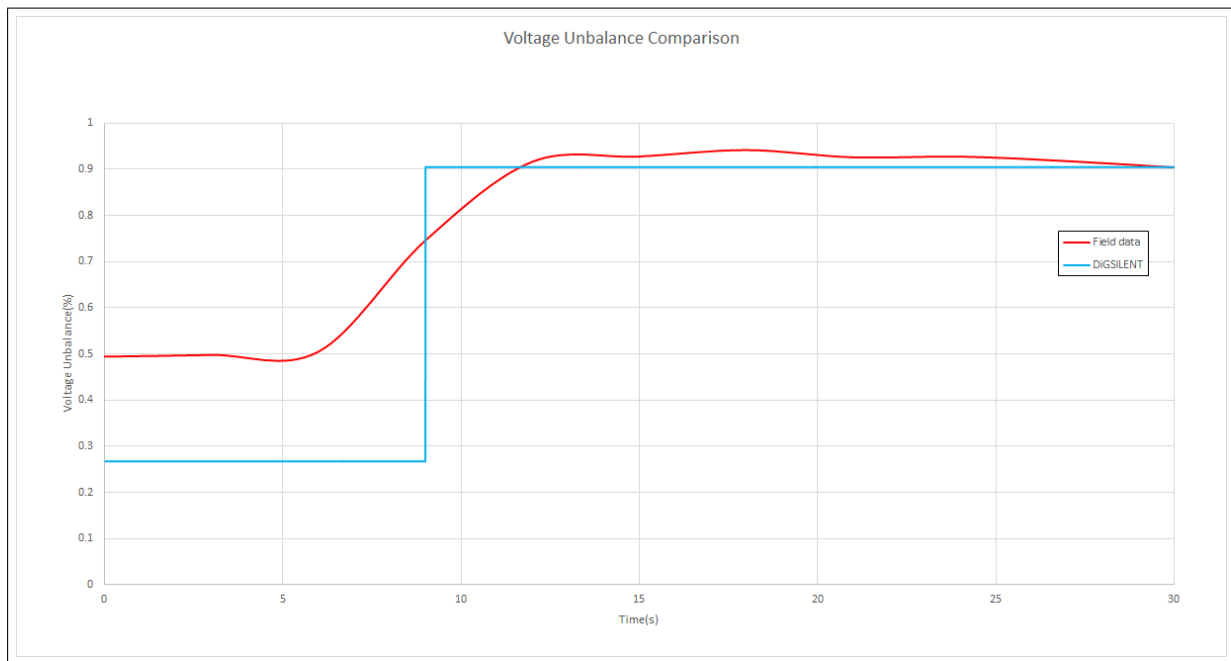


Figure 4.15: Islanding voltage unbalance comparison

All PV and ESS field data available shows these sources as voltage following (current sources), so transient current events experienced will be reviewed for model validation.

As discussed in section 4.3 the PV inverters have curtailment functionality when operating in islanded mode. PV curtailment only occurs when a surplus of energy is expected within the system, to protect the generator from backfeeding current.

This curtailing response provides a valuable current event that can be used to evaluate inverter control and operation as a current source. Figure 4.16 and 4.17 depict both the generator and PV inverter current produced during this event.

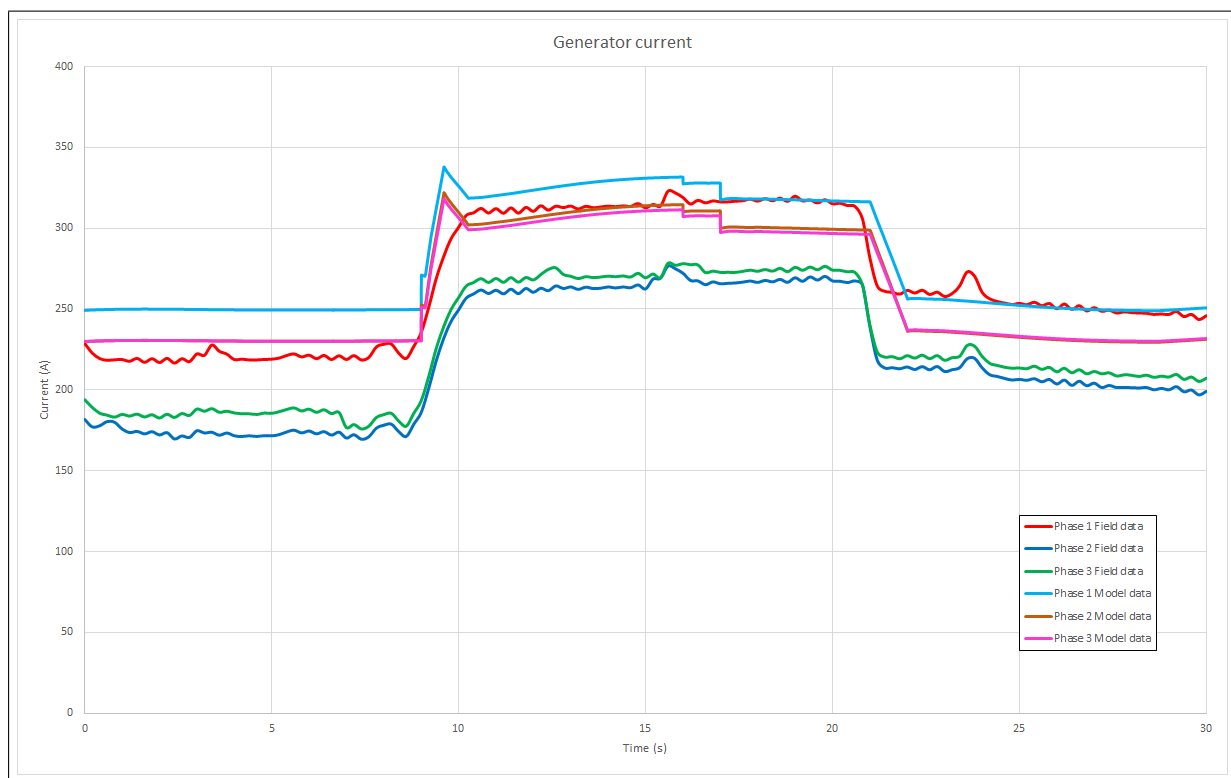


Figure 4.16: Islanded generator current output

While the generator is operating close to its minimum operating level, the PV inverters produce very little to no current (curtailed). Once the system bus is sufficiently loaded, with no danger of backfeeding energy to the generator, the PV inverters once again operates normally.

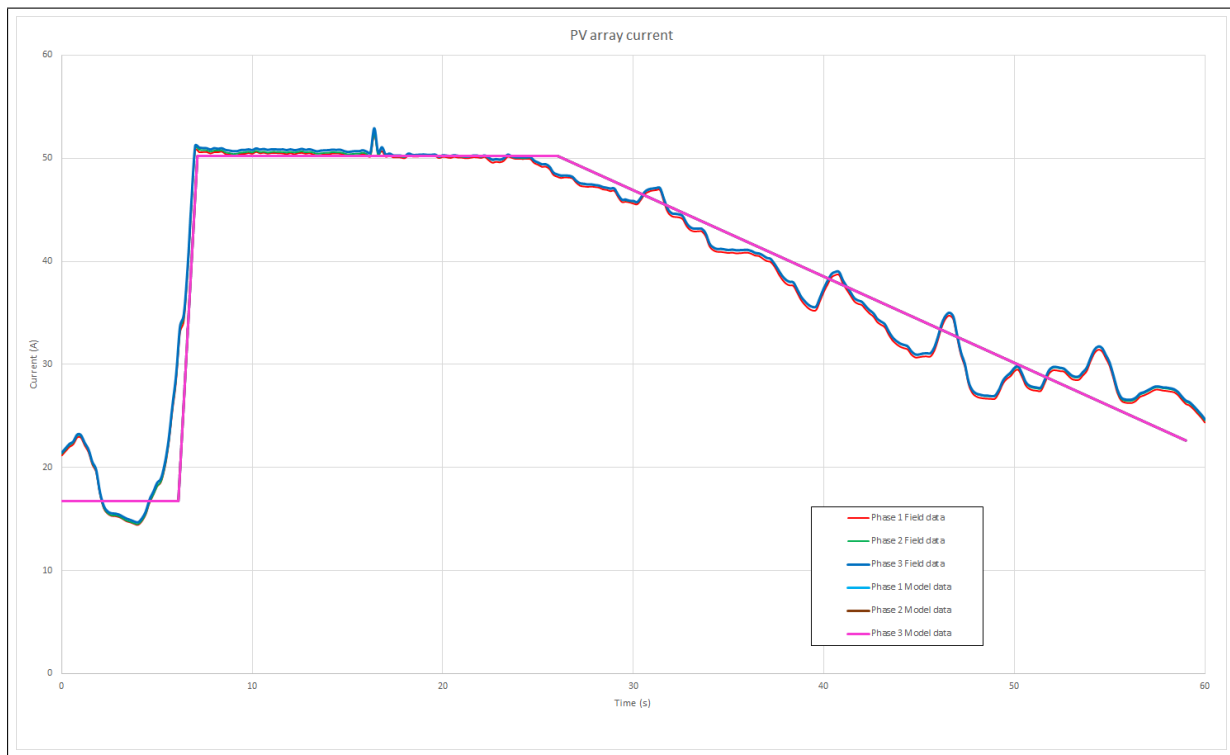


Figure 4.17: Islanded PV current output

A PV plant operating cycle, curtailment to normal operation and back to curtailment, is shown in figure 4.17. Comparing figure 4.16 and 4.17 shows the difference in response between the PV plant and the diesel generator. The PV inverters ramp down to curtailment level when the load decreases. The response delay observed prevents oscillatory behaviour between the PV plant and diesel generator. The diesel generator immediately adapts to the change in loading, balancing load and demand.

A discharge of 25 kVA from the battery storage during islanded is shown in figure 4.18.

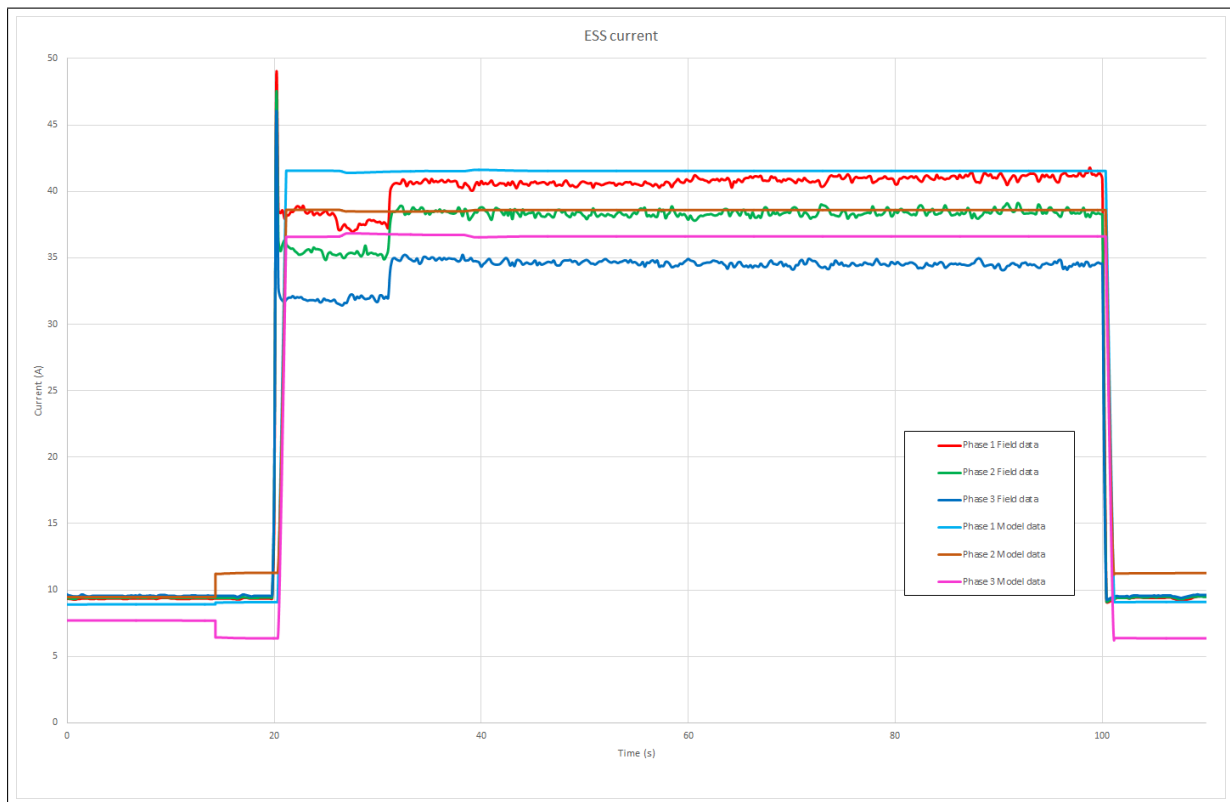


Figure 4.18: Islanded ESS current output

Field and simulation data follows the same ramp-up and ramp-down characteristics.

### 4.5.2 Grid-tied operation

Significant voltage events could not be emulated during grid-tied conditions by switching energy resources within the micro-grid. Supply impedance is much lower compared to the islanded condition and frequency remained perfectly controlled as the amount of inertia in the grid by far exceeds the inertia of the diesel generator.

With the low impedance and large amount of inertia that the grid provides, no value is gained by comparing and analysing field and simulation voltage trends while being grid-tied. During the measuring period, no significant voltage events occurred which would be able to substitute this lack of validation data and thus voltage transients was

not taken into account for grid-tied validation.

## 4.6 Conclusion

Assessment of power quality in the micro-grid under islanded condition remained well within the NRS 048 part 2-2015 requirements on compatibility.

Both steady-state operation and dynamic conditions resulting from emulating significant load changes were used to validate the results obtained by software (DIgSILENT PowerFactory) simulation. It is concluded that the modelling strategy and models used in the network model sufficiently predict the dynamic response of the reference microgrid. Useful results can be obtained by simulation when designing a microgrid.

Opportunities for improving control and utilization of both the ESS and PV inverter was identified.

# Chapter 5

## Discussion of Results

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*Opportunities for improving the microgrid performance under steady-state and dynamic conditions are analysed. Using the validated software model, these scenarios are tested and results interpreted.*

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### 5.1 Introduction

As discussed in chapter 1 microgrids incorporate various differences that increase their effective implementation difficulty. By analyzing field data certain operational shortcomings can be identified and using the model created in chapter 3 possible improvements can be tested.

### 5.2 Opportunities to improve microgrid performance

**Generator** - The generator voltage setpoint can be increased beyond the nominal voltage in use at the moment. It will enhance voltage stability when the microgrid

transition from grid-connected to islanded condition and support the energization of rotating loads (such as the compressor). Residual voltage during startup will be higher.

The generator Automatic Voltage Regulator (AVR) does fulfil operational requirements by regulating voltage within the stipulated margin as discussed in section 4.3.1, but its control parameters can be improved to ensure faster response to transient voltage events, such as voltage dips due to significant load steps. By improving the AVR operation larger transient loading events can be handled without any risk to plant operation.

**Energy storage system** - The battery storage resource can be deployed much better (having discharge capability of 275 kVA). When the production plant operates within peak tariffs the ESS should discharge and charge again in low tariff periods throughout the day. This is currently deployed and provides substantial economic benefits but does not allow the microgrid to provide the network flexibility that it could.

A high number of voltage dips in the utility network is characteristic of the area where the microgrid is located. If the battery storage system response time is fast enough, reactive power support can negate certain voltage dip events at the production facility. This will require continuous grid-connected operation of the battery storage system. Also, during the transition to islanded mode, the ESS can be used in a UPS configuration by delivering full capacity to support critical loads until the diesel-generator can take over. Depending on the time of the day, the PV plant could already be contributing.

To ensure that the ESS can provide stability support in any situation, it should be able to charge and discharge in both islanded and grid-tied operation.

**Photovoltaic array** - The PV plant is the main contributor to the microgrid's green and economic operation. It is thus ideal for the PV plant to produce the maximum amount of energy possible at all times (peak power production at 200 kW).

Curtailment is a safety measure but can be a waste of energy if not incorporated smartly.

Except for curtailing to protect the generator, the microgrid curtails its PV when it provides surplus energy in grid-tied operation. This is due to a municipal contract that prohibits any excess energy to be injected into the municipal network. Instead of the PV curtailing the ESS can absorb this power by charging. Only when the ESS is fully charged, curtailment should be an option. This allows the battery storage to be used more proactively (with its 400 kWh capacity).

**Load** - Incorporating load shedding within the system is planned, but has not been implemented at the time of the field data measurement. Segmental load shedding will ensure that the system operates below its limit in islanded mode and can be a good method to limit generator use, which is economically costly.

### 5.3 Improvements

**Generator** - To improve the generator operation the PID controller used for field voltage regulation was tuned to have an aggressive product-, moderate derivative- and small integration coefficient. The islanded voltage set point was raised to 1.03 p.u. which provides a buffer for unexpected load steps.

Functionality was added to improve planned islanding and load steps, which boosts reactive power 4 seconds before the planned switch takes place, drastically decreasing voltage dips experienced. Figure 5.1 and 5.2 depicts the average RMS voltage experienced during a planned islanding and unexpected load step, with only the generator operational in islanded mode.

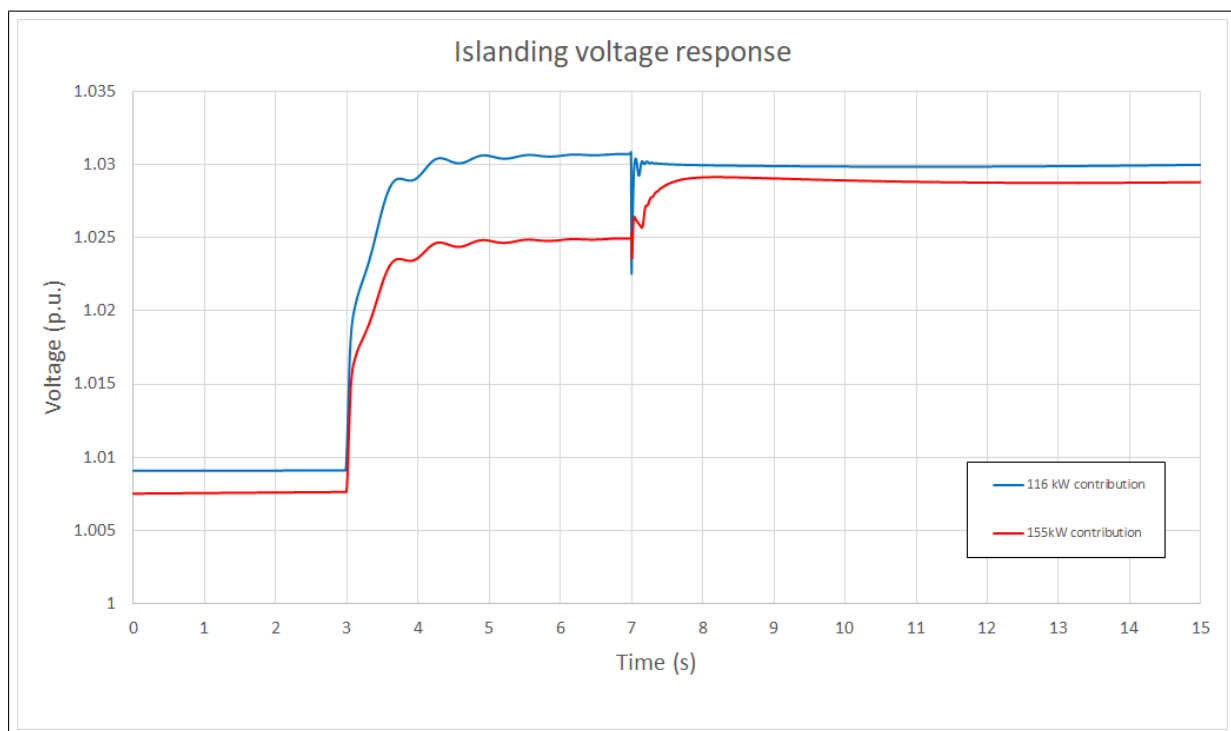


Figure 5.1: Voltage reaction during planned islanding.

Note that the step values listed in the legend of figure 5.2 are merely the initial step where after these values are increased with 250 % over a 0.5 s period (i.e. a 25 kW, 5 kvar step becomes 75 kW and 12.5 kvar). With the 75 kW step in figure 5.2 the generator operated at its maximum output, and can not keep the frequency from dropping to 48.25 Hz (a simulated operating limit).

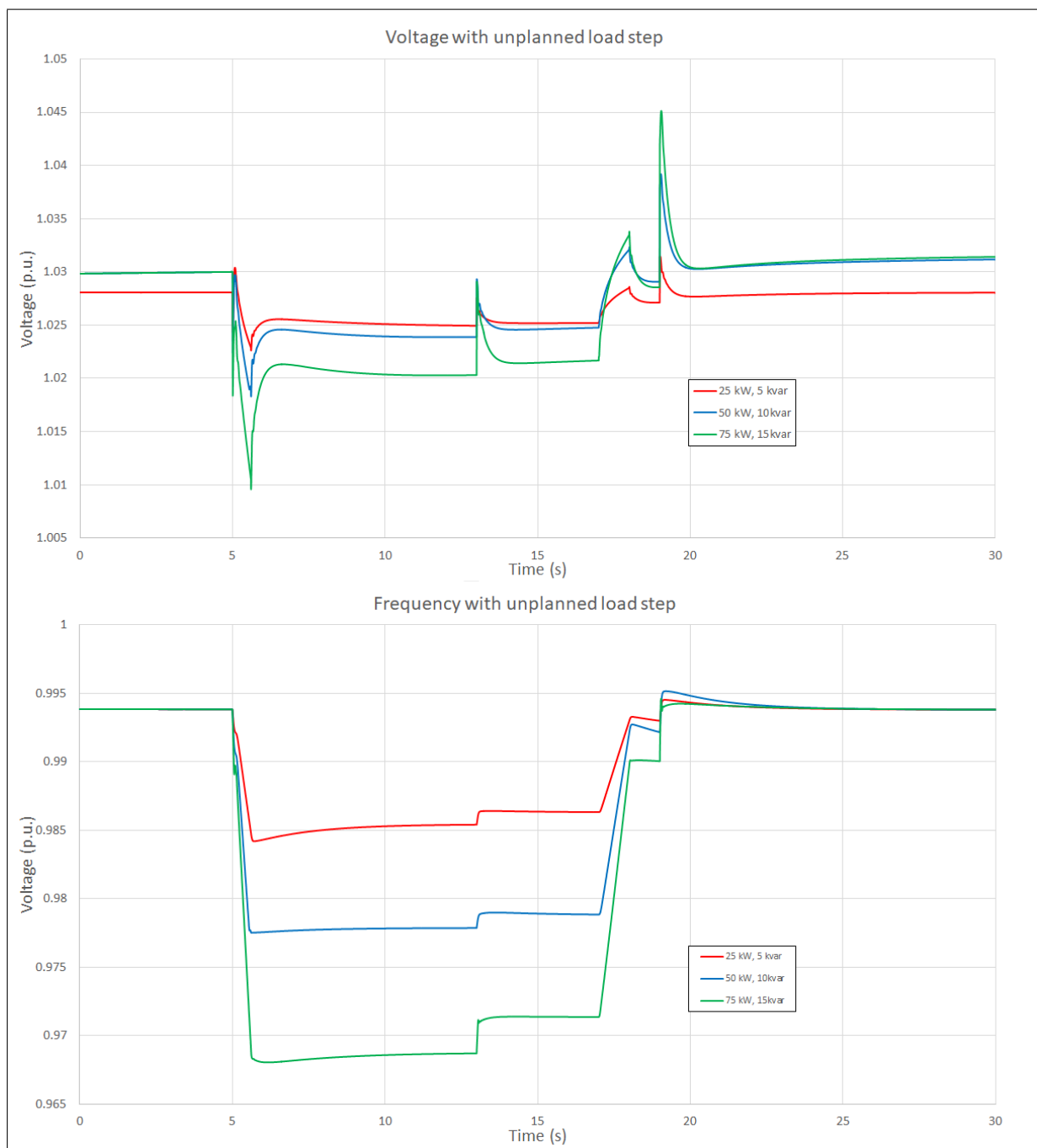


Figure 5.2: Voltage reaction during unplanned load step.

Figure 5.3 shows the improved power contribution philosophy of the generator. Synchronization to the network takes place at 10 seconds and a planned islanding event at 33 seconds.

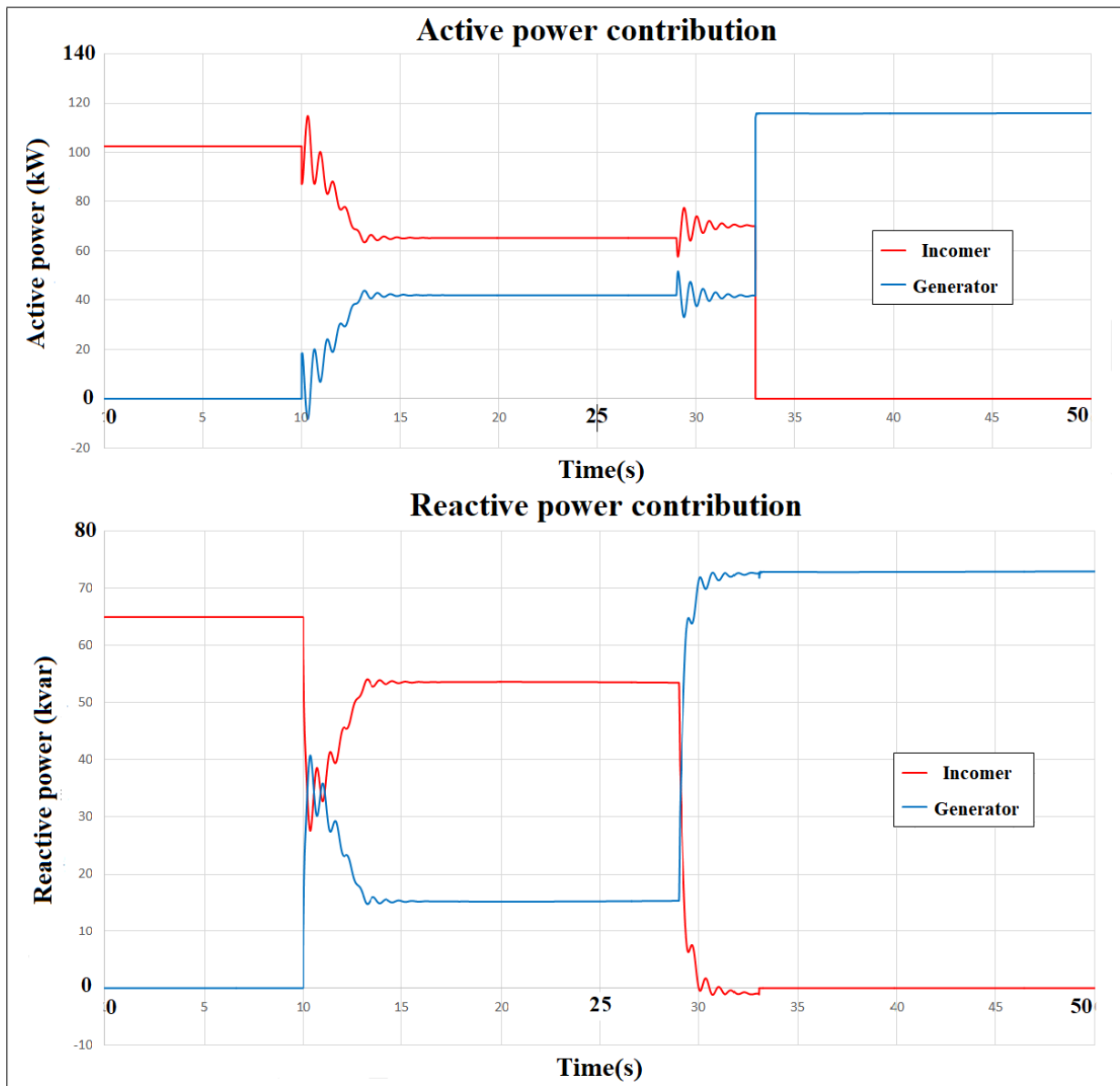


Figure 5.3: Power contribution philosophy for planned islanding.

Increasing the diesel generator's reactive power production (lowering the incomer contribution close to 0 kvar) 4 seconds before islanding takes place, drastically reduces voltage sag experienced directly after islanding takes place.

**Energy storage system** - ESS discharge gradient, response time and capacity were taken into account for its voltage and frequency support application. For simulations,

the ESS was limited to a 100 kW and 50 kvar discharge respectively. A response time of 40 ms was selected and a reset time of 5 seconds (started when frequency and voltage return to acceptable operating levels).

ESS active power discharge starts after the frequency drops below 49 Hz (for a selected time constant) to boost the frequency back to acceptable levels. The reactive power boosts to stabilize voltage after bus voltage drops below 0.93 p.u. (for a selected time constant). The opposite is true if frequency increases to 51 Hz or voltage to 1.07 p.u. for the selected time constant.

Figure 5.4 shows an example of this voltage and frequency support method.

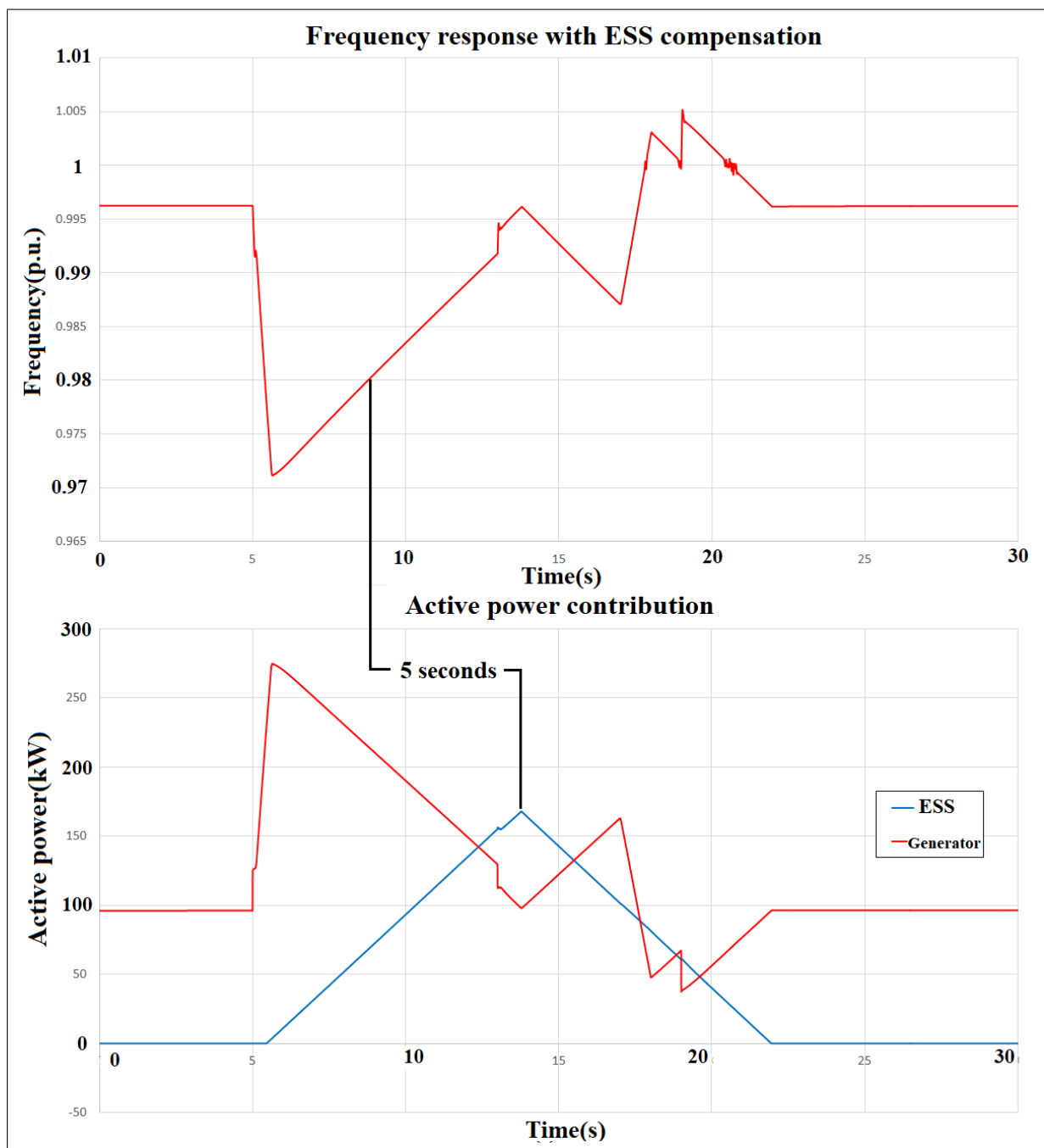


Figure 5.4: ESS frequency dip compensation.

When the diesel generator reaches its operating limit and the frequency drops below the set threshold of 49 Hz (0.98 p.u.) the ESS steadily starts boosting and recedes once the frequency is within operational limits for 5 seconds.

**Photovoltaic array** - Curtailment of the PV plant is modified to ensure that the maximum amount of renewable energy is used. Figure 5.5 shows the power management of the generator, PV and ESS before and after modification to curtailment control.

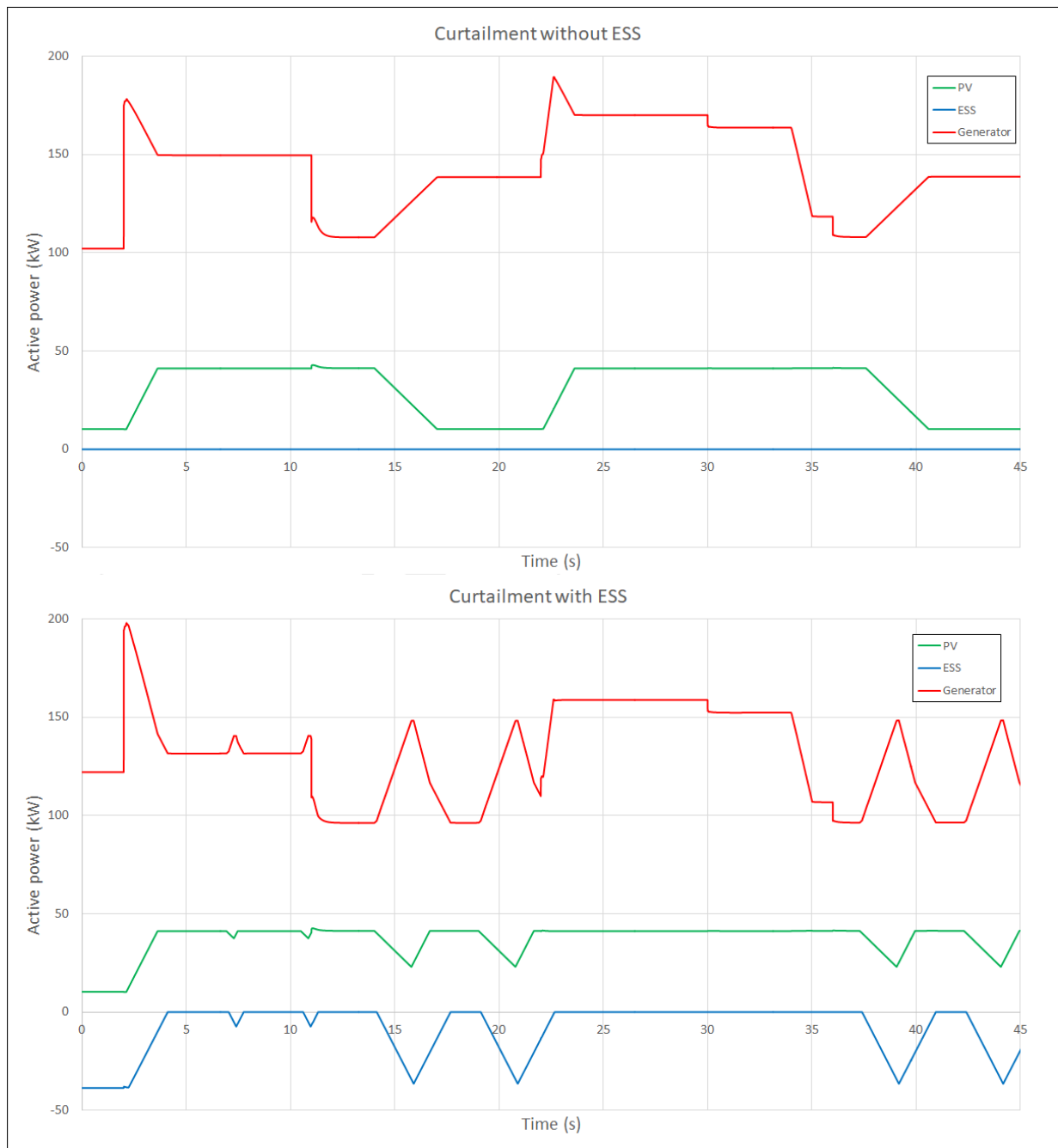


Figure 5.5: PV and ESS operation during curtailment.

The simulation was done on the edge of the curtailment threshold, which is the reason for the constant ESS activity and a good example of the active control taking place. Curtailment will still take place when the ESS is fully charged (according to battery specifications).

**Load** - Figure 5.6 shows the implementation of load shedding, using the same 75 kW step shown in figure 5.2, as an unnecessary 47 kVA is shed. This takes place during islanded mode, with a response time of 5 cycles. Load shedding is initialized once the frequency drops below 49 Hz.

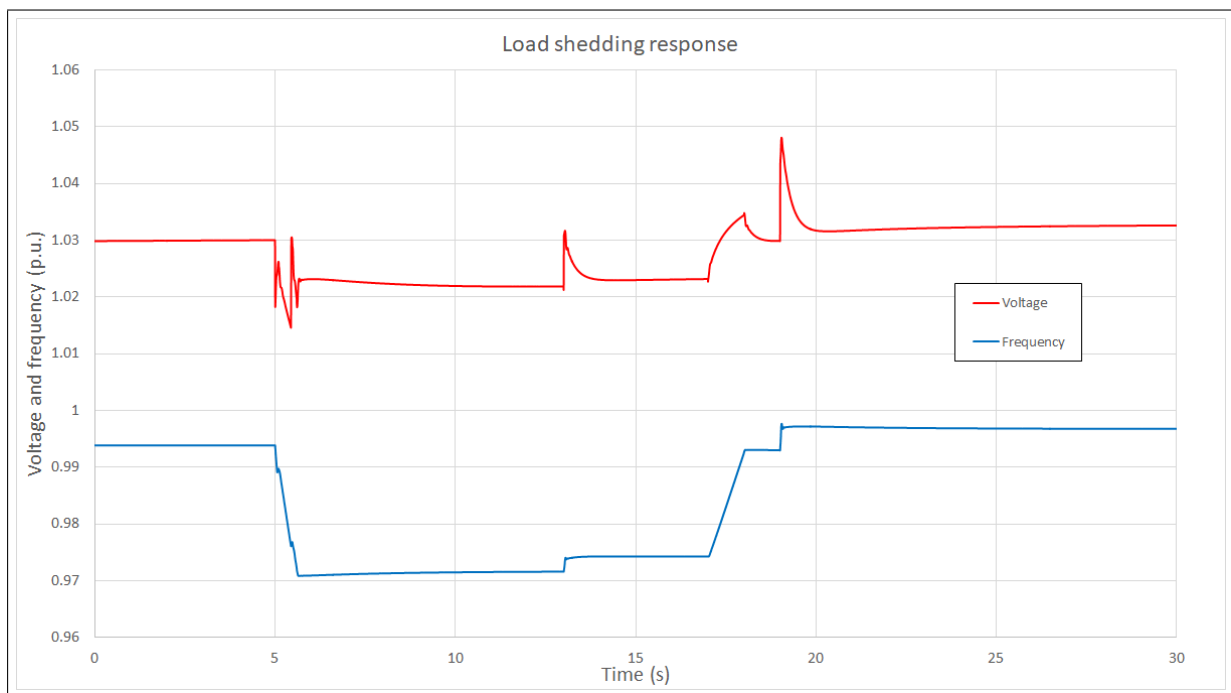


Figure 5.6: Load shedding response on frequency and voltage.

A load of 47 kVA is relatively small in this system (+10 % of full load), but does have a significant effect. The frequency only drops to 48.55 Hz, which is within tolerable limits, while initial voltage transients are not as large in amplitude. Well planned load shedding philosophy and categories have a significant positive effect within any power system, when necessary. Ideally, load shedding should not be the first response but

rather used when necessary to ensure stable operation.

## 5.4 Conclusion

The available field data was analysed and various possible microgrid operating improvements were identified. These improvements were all observable in the transient domain and the model validated in chapter 4 was used to implement them.

Suggested improvements were tested with different model setpoints and scenarios. Some of these results were shown in section 5.3 and provided an account of the dynamic response improvement.

The results obtained are valuable as they justify chapter 1's statement that accurate models can be used to test improvements and proclaims the importance of having a representative dynamic model of a microgrid power system.

# Chapter 6

## Conclusion

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*Chapter 6 evaluates the research outcome and propose future opportunities.*

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### 6.1 Dissertation findings

Academic publications on microgrids are increasing, reporting opportunities for an economically beneficial and environmentally friendly power system. All over, cost, voltage reliability and quality are becoming more and more important for users.

In Southern Africa, electricity regulators do not adequately protect the users and at the same time, utilities have to increase prices as networks age and require upgrades. Maintenance is higher than before and technical skills levels did not grow as needed. This provides an ideal environment for microgrid development and testing.

Configuration, of energy resources within a specific microgrid and how these components participate are not standardized. Standards organizations such as IEC and IEEE are working on this. Much research and development are still needed.

With this wave of development diverse configurations exist for microgrid components, objectives and control strategies. This allows for many challenges in developing microgrids to address the needs users have in the industry, commerce, agricultural and other sectors. One of the best tools for addressing these challenges is the use of a model that can produce reliable system dynamic response results during the microgrid design, implementation and improvement process.

With the main interface between the energy resource and the microgrid being power electronics, special consideration is needed related to voltage quality and stability. Dynamic conditions have to be included during modelling and simulation studies.

Using DigSILENT's PowerFactory simulation environment in conjunction with authoritative academic literature and field data recorded in an industrial LV microgrid, a representative model was developed. The ability to simulate the dynamic response of the microgrid correctly was verified by comparing the performance to similar work reported by peer-reviewed academic publications. Different dynamic conditions were then emulated in a real microgrid and using this field data, the simulation model was validated. Various scenarios were then simulated and the usefulness of the software model demonstrated by adjusting the control methodology in the microgrid for improved performance.

The methodology used provided accurate results but due to limited operational data and some DER uncertainties (protected by intellectual property), the time needed to follow this approach was extended. Better information gathering agreements with the owner of any microgrid being modelled are necessary to prevent unnecessary delays and to provide even better results.

By verifying the model and development approach through literature and case studies, and validating its output with field data makes the process and model a trusted tool in future development. This method of verification provides a model standard agreement with the rest of the academic community while ensuring reproducibility in the future. Comparing field data to the simulated results provides a method of model validation

in spite of the lack in technical system information present during model development.

## 6.2 Future work

It is possible that voltage quality in a microgrid is compromised due to the higher level of harmonic currents resulting from the power electronic interfaces needed to integrate i.e. a PV source and battery storage. In addition, the fault level in the microgrid is lower compared to when connected to the distribution grid, resulting in harmonic currents in a microgrid causing comparatively higher harmonic voltage drops, consequently a higher voltage THD.

Comprehensive modelling of harmonics within a microgrid has to be included during modelling and the optimal approach to containing voltage THD, identified. Active harmonic filtering is expensive and the performance of passive filters have to be studied for optimal performance.

Direct-startup of rotating loads in a microgrid can cause deeper dips compared to when distribution grid connected. Active voltage conditioning can be needed to mitigate this disadvantage.

Transition to and from islanded mode of operation has to be improved as the voltage reference in the islanded condition will not be synchronous to the distribution network voltage signal. Also, future power systems can require a number of microgrids to collaborate in objectives such as energy arbitrage, requiring synchronization and optimal approaches to energy exchange.

Future distribution systems will have to include smart microgrid solutions since cost, reliability and PQ will stimulate users to consider self-generation, local storage and local conditioning of voltage quality.

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# Appendix A

## DIgSILENT PowerFactory technical implementation

DIgSILENT is a powerful simulation environment which enables the user to complete complex analysis of power systems through the practice of simulation. Due to the software's specific target market as well as its specialized area of application, a lack in user-based support is prevalent. The following appendix acts as a guide on how the DIgSILENT model in chapter 3 was created.

This guide should be used in parallel with the DIgSILENT user manual.

### A.1 Structure

For any transient simulation that utilizes any of the possible control methods that DIgSILENT supports, a proper model structure is necessary. Within the project directory, which can be accessed using the data manager (top left of toolbar), the main two folders used to create the control structure is the 'Library' and 'Network Model' folders. The steps to populate these folders are listed below.

- 
1. Library > User Defined Models - Create a model frame which will act as a schematic representation of the control utilized by the model.
  2. Network Model > Network Data > Grid - Create a composite model that will tie the various control elements together. Within this composite model refer to the model frame created in 1, and press 'Slot Update'.
  3. Network Model > Network Data > Grid > Composite model - Create common models.
  4. Library > User Defined Models - Create block definitions.

Within the model frame created in step 1, slots should be used to represent the various network components, measuring points and control modules needed for the project. In these slots, signals (which are defined by right-clicking on elements within data manager and then selecting "define for RMS/EMT simulation") can be allocated and connected to the various other slots on the frame. It is important to note that exactly the same signal name as the defined variable (such as "u" for per unit voltage magnitude) should be used in slots, but that slots should not be connected to corresponding block definitions through this interface.

Once the composite model in step 2 has been created, connected to the model frame and the slots updated, slot allocation can begin. The various slots that represent components depicted in the Single Line Diagram (SLD) or measurement equipment defined in the network model can be connected to their representative slots by selecting the corresponding "Net Element" tab and browsing the data manager to the desired selection. Note that valid selections are marked with a tick.

For the allocation of control slots, step 3 is needed. Selecting the composite model through the data manager, common models can be created. For each control slot within the model frame, a common model should be created. These common models provide an interface to update various declared parameters and tables and act as the gateway between the DSL code and the components depicted on the model frame. Once all

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common models are created within the composite model and connected to their corresponding slot, step 4 can be started.

The block definitions created in step 4 act as the intelligence core for the various control modules included in the model frame. All inputs and outputs should be defined, as defined within the slot interface of the model frame. Furthermore, any parameters and limiting variables that should be visible within the common model, as well as state and internal variables used in the DSL code, should also be defined here.

With this structure successfully created and programming correctly done, RMS and EMT simulations should execute without error.

## **A.2 Simulation programming**

To view the available functions and correct initialization practice for variables within DSL refer to section 28 "RMS/EMT Simulations" and 29 "Models for Dynamic Simulations" within the PowerFactory user manual.

Important to note is that a state variable should be defined for every derivative and/or integration done within the simulation program. These state variables should be initialized twice within the DSL code, once as the original statement "x1" and once as the derived statement "x1.", to ensure correct mathematical execution.

Once the simulation programming is complete according to convention stipulated in the user manual, simulation parameters can be set. This is done in the middle of the top toolbar. Note that although only RMS or EMT simulations are done any and all selections done within this settings window should be reflected in the load flow parameter selection window to ensure correct initialization and operation.

# **Appendix B**

## **Field test documentation**

The following document provides a detailed account of tests done on the 8th of June 2018 to obtain field data used to validate the model developed in chapter 4.

# Transient data test plan – Microgrid

Date: 2018/06/08

Location:  Wadeville, Johannesburg, South Africa

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| 3.    | Test Procedure according to time stamp    | 26 |

## 1. PRE-TEST CHECKS

The tests should not take place if any item of plant is in a condition which could endanger the Plant, Plant Personnel or result in a test failure. The following Pre-Test Checklist gives items of plant should be checked prior to the tests being done and these checks should be signed off (name included).

| System Description                                                                                                                                                                                                                                                                                                                 | Yes | No | STATION   |      |
|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----|----|-----------|------|
| <b>Power supply to Vecto II meters:</b> Ensure power supply to each Vecto II meter from the UPS distribution board in the substation room.                                                                                                                                                                                         |     |    | SIGNATURE |      |
|                                                                                                                                                                                                                                                                                                                                    |     |    | NAME      | DATE |
| <b>Generator Incomer Panel:</b> Ensure that Vecto II measurement device is correctly connected to the back of the generator incomer panel, voltage leads terminated to the fuses, and current leads attached to current transducers clamped around incoming phases.                                                                |     |    | SIGNATURE |      |
|                                                                                                                                                                                                                                                                                                                                    |     |    | NAME      | DATE |
| <b>LV Incomer 1:</b> Ensure that Vecto II measurement device is correctly connected to the control panel at the front of the LV incomer 1 panel; voltage leads terminated to the "Mains" sliding link terminal blocks, and current leads clamped to the CT inputs to the ComAp IM-NTC-BB IntelliMains Controller. Refer to Fig 1.  |     |    | SIGNATURE |      |
|                                                                                                                                                                                                                                                                                                                                    |     |    | NAME      | DATE |
| <b>PV Incomer Panel:</b> Ensure that Vecto II measurement device is correctly connected to the control panel at the front of the PV Incomer panel; voltage leads terminated to the "Mains" terminal blocks using "pig tails", and current leads clamped to the CT inputs to the ComAp IS-NTC-InteliHybrid Controller.              |     |    | SIGNATURE |      |
|                                                                                                                                                                                                                                                                                                                                    |     |    | NAME      | DATE |
| <b>Storage Incomer Panel:</b> Ensure that Vecto II measurement device is correctly connected to the control panel at the front of the PV Incomer panel; voltage leads terminated to the "Mains" terminal blocks using "pig tails", and current leads clamped to the CT terminal block.                                             |     |    | SIGNATURE |      |
|                                                                                                                                                                                                                                                                                                                                    |     |    | NAME      | DATE |
| <b>Pre-test current phasor measurement:</b> Before the official test procedure is started the direction of current phasors should be measured and confirmed to be correct. This is done by supplying the LV network with current from each source and then digitally correcting any faults before disconnecting that source again. |     |    | SIGNATURE |      |
|                                                                                                                                                                                                                                                                                                                                    |     |    | NAME      | DATE |

| System Description                                                                                                                                                                                                                                                                                                                                                          | Yes | No | STATION   |      |
|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----|----|-----------|------|
| <b>Low resolution continuous measurements:</b><br>Ensure that Vecto II measurement devices are set up to record low resolution measurement data (3s) for the duration of the test period. Verify that the data is being measured and recorded at each Vecto II. Verify that the triggering of the high resolution event data in no way impacts the continuous measurements. |     |    | SIGNATURE |      |
|                                                                                                                                                                                                                                                                                                                                                                             |     |    | NAME      | DATE |
| <b>Compressor/Step load operation:</b> As the compressor is constantly in operation it will not be switched manually. After each transition the network will be left in that state for some time to give the compressor time to cycle its operation.                                                                                                                        |     |    | SIGNATURE |      |
|                                                                                                                                                                                                                                                                                                                                                                             |     |    | NAME      | DATE |
| <b>Charge during diesel generator operation:</b><br>Initially a charge state would have been tested during operation of generator. This was found not to be possible and was left out of tests.                                                                                                                                                                             |     |    | SIGNATURE |      |
|                                                                                                                                                                                                                                                                                                                                                                             |     |    | NAME      | DATE |



Figure 1: Installation of Vecto II on Incomer 1

## 2. GRID TIED SYSTEM TESTS

### 2.1 GRID TIED TESTS AT LOAD 200 KW

#### 2.1.1 Transition State to Grid-tied Test State

| Step | Description                                                                                                                                              | Feedback | Time |
|------|----------------------------------------------------------------------------------------------------------------------------------------------------------|----------|------|
| 1.   | <b>Plant unit is online and load is approx. 120kW</b>                                                                                                    |          |      |
| 1.1. | Plant is grid-tied, with LV incomer 1 breaker closed.                                                                                                    |          |      |
| 1.2. | PV plant is online, with PV incomer breaker closed.                                                                                                      |          |      |
| 1.3. | Storage plant is online with Storage static switch closed.                                                                                               |          |      |
| 1.4  | Diesel genset plant is offline with Diesel generator incomer breaker open.                                                                               |          |      |
| 1.5  | Compressor plant is online and drawing load.                                                                                                             |          |      |
| 2.   | On confirmation by <i>STATION</i> Personnel and the <i>TESTING TEAM</i> that the above conditions are satisfied, the further testing shall be performed. |          |      |
| 3.   | <b>Initiate the ‘Open breaker’ command on the IS-NTC-Hybrid controller panel</b>                                                                         |          |      |
| 4.   | <b>Open static switch in the battery inverter cabinet via the HMI operator workstation</b>                                                               |          |      |

### 2.1.2 Transition State to PV ON

| Step | Description                                                                                                                                              | Feedback | Time |
|------|----------------------------------------------------------------------------------------------------------------------------------------------------------|----------|------|
| 1.   | <b>Plant unit is online and load is approx. 200kW</b>                                                                                                    |          |      |
| 1.1. | Plant is grid tied, with LV incomer 1 breaker closed.                                                                                                    |          |      |
| 1.2. | PV plant is offline, with PV incomer breaker open.                                                                                                       |          |      |
| 1.3. | Storage plant is offline with Storage static switch open.                                                                                                |          |      |
| 1.4  | Diesel genset plant is offline with Diesel generator incomer breaker open.                                                                               |          |      |
| 1.5  | Compressor plant is online and drawing load.                                                                                                             |          |      |
| 2.   | On confirmation by <i>STATION</i> Personnel and the <i>TESTING TEAM</i> that the above conditions are satisfied, the further testing shall be performed. |          |      |
| 3.   | <b>Initiate the 'Close breaker' command on the IS-NTC-Hybrid controller panel</b>                                                                        |          |      |

### 2.1.3 Transition State to Storage: Charge 50kW

| Step | Description                                                                                                                                              | Feedback | Time |
|------|----------------------------------------------------------------------------------------------------------------------------------------------------------|----------|------|
| 1.   | <b>Plant unit is online and load is approx. 200kW</b>                                                                                                    |          |      |
| 1.1. | Plant is grid tied, with LV incomer 1 breaker closed.                                                                                                    |          |      |
| 1.2. | PV plant is online, with PV incomer breaker closed.                                                                                                      |          |      |
| 1.3. | Storage plant is idle with Storage static switch open.                                                                                                   |          |      |
| 1.4. | Diesel genset plant is offline with Diesel generator incomer breaker open.                                                                               |          |      |
| 1.5. | Compressor plant is online and drawing load.                                                                                                             |          |      |
| 2.   | On confirmation by <i>STATION</i> Personnel and the <i>TESTING TEAM</i> that the above conditions are satisfied, the further testing shall be performed. |          |      |
| 3.   | <b>Set storage system to 'Charge' via HMI operator workstation. Refer to Fig 2.</b>                                                                      |          |      |
| 4.   | <b>HMI closes static switch in battery inverter cabinet.</b>                                                                                             |          |      |
| 5.   | <b>Charge of 50kW commence.</b>                                                                                                                          |          |      |



Figure 2: HMI for Controlling Storage System

#### 2.1.4 Transition State to Storage: Idle

| Step | Description                                                                                                                                              | Feedback | Time |
|------|----------------------------------------------------------------------------------------------------------------------------------------------------------|----------|------|
| 1.   | <b>Plant unit is online and load is approx. 200kW</b>                                                                                                    |          |      |
| 1.1. | Plant is grid tied, with LV incomer 1 breaker closed.                                                                                                    |          |      |
| 1.2. | PV plant is online, with PV incomer breaker closed.                                                                                                      |          |      |
| 1.3. | Storage plant is charging with Storage static switch closed.                                                                                             |          |      |
| 1.4  | Diesel genset plant is offline with Diesel generator incomer breaker open.                                                                               |          |      |
| 1.5  | Compressor plant is online and drawing load.                                                                                                             |          |      |
| 2.   | On confirmation by <i>STATION</i> Personnel and the <i>TESTING TEAM</i> that the above conditions are satisfied, the further testing shall be performed. |          |      |
| 3.   | <b>Set storage system to 'Idle' via HMI operator workstation.</b>                                                                                        |          |      |
| 4.   | <b>HMI opens static switch in battery inverter cabinet.</b>                                                                                              |          |      |
| 5.   | <b>Storage system in idle.</b>                                                                                                                           |          |      |

### 2.1.5 Transition State to Storage: Discharge

| Step | Description                                                                                                                                              | Feedback | Time |
|------|----------------------------------------------------------------------------------------------------------------------------------------------------------|----------|------|
| 1.   | <b>Plant unit is online and load is approx. 200kW</b>                                                                                                    |          |      |
| 1.1. | Plant is grid tied, with LV incomer 1 breaker closed.                                                                                                    |          |      |
| 1.2. | PV plant is online, with PV incomer breaker closed.                                                                                                      |          |      |
| 1.3. | Storage plant is idle with Storage static switch open.                                                                                                   |          |      |
| 1.4  | Diesel genset plant is offline with Diesel generator incomer breaker open.                                                                               |          |      |
| 1.5  | Compressor plant is online and drawing load.                                                                                                             |          |      |
| 2.   | On confirmation by <i>STATION</i> Personnel and the <i>TESTING TEAM</i> that the above conditions are satisfied, the further testing shall be performed. |          |      |
| 3.   | <b>Set storage system to 'Discharge' via HMI operator workstation.</b>                                                                                   |          |      |
| 4.   | <b>HMI closes static switch in battery inverter cabinet.</b>                                                                                             |          |      |
| 5.   | <b>Discharge of 50kW commence.</b>                                                                                                                       |          |      |

### 2.1.6 Transition State to Storage: Idle

| Step | Description                                                                                                                                              | Feedback | Time |
|------|----------------------------------------------------------------------------------------------------------------------------------------------------------|----------|------|
| 1.   | <b>Plant unit is online and load is approx. 200kW</b>                                                                                                    |          |      |
| 1.1. | Plant is grid tied, with LV incomer 1 breaker closed.                                                                                                    |          |      |
| 1.2. | PV plant is online, with PV incomer breaker closed.                                                                                                      |          |      |
| 1.3. | Storage plant is discharging with Storage static switch closed.                                                                                          |          |      |
| 1.4  | Diesel genset plant is offline with Diesel generator incomer breaker open.                                                                               |          |      |
| 1.5  | Compressor plant is online and drawing load.                                                                                                             |          |      |
| 2.   | On confirmation by <i>STATION</i> Personnel and the <i>TESTING TEAM</i> that the above conditions are satisfied, the further testing shall be performed. |          |      |
| 3.   | <b>Set storage system to 'Idle' via HMI operator workstation.</b>                                                                                        |          |      |
| 4.   | <b>HMI opens static switch in battery inverter cabinet.</b>                                                                                              |          |      |
| 5.   | <b>Storage system in idle.</b>                                                                                                                           |          |      |

### 2.1.7 Transition State to Diesel ON

| Step | Description                                                                                                                                              | Feedback | Time |
|------|----------------------------------------------------------------------------------------------------------------------------------------------------------|----------|------|
| 1.   | <b>Plant unit is online and load is approx. 200kW</b>                                                                                                    |          |      |
| 1.1. | Plant is grid tied, with LV incomer 1 breaker closed.                                                                                                    |          |      |
| 1.2. | PV plant is online, with PV incomer breaker closed.                                                                                                      |          |      |
| 1.3. | Storage plant is idle with Storage static switch open.                                                                                                   |          |      |
| 1.4. | Diesel genset plant is offline with Diesel generator incomer breaker open.                                                                               |          |      |
| 1.5. | Compressor plant is online and drawing load.                                                                                                             |          |      |
| 2.   | On confirmation by <i>STATION</i> Personnel and the <i>TESTING TEAM</i> that the above conditions are satisfied, the further testing shall be performed. |          |      |
| 3.   | <b>Place IM-NTC-BB IntelliMains NT controller in manual mode. Refer to Fig 3.</b>                                                                        |          |      |
| 4.   | <b>Place IG-NTC-BB IntelliGen NT controller in manual mode.</b>                                                                                          |          |      |
| 5.   | <b>Press the ‘Start’ green push button on the IntelliGen NT controller panel</b>                                                                         |          |      |
| 6.   | <b>Initiate the ‘Close breaker’ command on the IntelliGen NT controller panel</b>                                                                        |          |      |



Figure 3: Synchronizing Generator to LV Network

### 2.1.8 Transition State to Storage: Discharge

| Step | Description                                                                                                                                              | Feedback | Time |
|------|----------------------------------------------------------------------------------------------------------------------------------------------------------|----------|------|
| 1.   | <b>Plant unit is online and load is approx. 200kW</b>                                                                                                    |          |      |
| 1.1. | Plant is grid tied, with LV incomer 1 breaker closed.                                                                                                    |          |      |
| 1.2. | PV plant is online, with PV incomer breaker closed.                                                                                                      |          |      |
| 1.3. | Storage plant is idle with Storage static switch open.                                                                                                   |          |      |
| 1.4  | Diesel genset plant is online with Diesel generator incomer breaker closed.                                                                              |          |      |
| 1.5  | Compressor plant is online and drawing load.                                                                                                             |          |      |
| 2.   | On confirmation by <i>STATION</i> Personnel and the <i>TESTING TEAM</i> that the above conditions are satisfied, the further testing shall be performed. |          |      |
| 3.   | <b>Set storage system to 'Discharge' via HMI operator workstation.</b>                                                                                   |          |      |
| 4.   | <b>HMI closes static switch in battery inverter cabinet.</b>                                                                                             |          |      |
| 5.   | <b>Discharge of 25kW commence.</b>                                                                                                                       |          |      |

### 2.1.9 Transition State to Storage: Idle

| Step | Description                                                                                                                                              | Feedback | Time |
|------|----------------------------------------------------------------------------------------------------------------------------------------------------------|----------|------|
| 1.   | <b>Plant unit is online and load is approx. 200kW</b>                                                                                                    |          |      |
| 1.1. | Plant is grid tied, with LV incomer 1 breaker closed.                                                                                                    |          |      |
| 1.2. | PV plant is online, with PV incomer breaker closed.                                                                                                      |          |      |
| 1.3. | Storage plant is discharging with Storage static switch closed.                                                                                          |          |      |
| 1.4  | Diesel genset plant is online with Diesel generator incomer breaker closed.                                                                              |          |      |
| 1.5  | Compressor plant is online and drawing load.                                                                                                             |          |      |
| 2.   | On confirmation by <i>STATION</i> Personnel and the <i>TESTING TEAM</i> that the above conditions are satisfied, the further testing shall be performed. |          |      |
| 3.   | <b>Set storage system to 'Idle' via HMI operator workstation.</b>                                                                                        |          |      |
| 4.   | <b>HMI opens static switch in battery inverter cabinet.</b>                                                                                              |          |      |
| 5.   | <b>Storage system in idle.</b>                                                                                                                           |          |      |

## 2.2 OFF-GRID TESTS AT LOAD 200 KW

### 2.2.1 Transition State to Islanded Operation

| Step | Description                                                                                                                                              | Feedback | Time |
|------|----------------------------------------------------------------------------------------------------------------------------------------------------------|----------|------|
| 1.   | <b>Plant unit is online and load is approx. 200kW</b>                                                                                                    |          |      |
| 1.1. | Plant is grid tied, with LV incomer 1 breaker closed.                                                                                                    |          |      |
| 1.2. | PV plant is online, with PV incomer breaker closed.                                                                                                      |          |      |
| 1.3. | Storage plant is idle with Storage static switch open.                                                                                                   |          |      |
| 1.4  | Diesel genset plant is online with Diesel generator incomer breaker closed.                                                                              |          |      |
| 1.5  | Compressor plant is online and drawing load.                                                                                                             |          |      |
| 2.   | On confirmation by <i>STATION</i> Personnel and the <i>TESTING TEAM</i> that the above conditions are satisfied, the further testing shall be performed. |          |      |
| 3.   | <b>Ensure IM-NTC-BB IntelliMains NT controller in manual mode</b>                                                                                        |          |      |
| 4.   | <b>Ensure IG-NTC-BB IntelliGen NT controller in manual mode</b>                                                                                          |          |      |
| 5.   | <b>Initiate the ‘Open breaker’ command on the IntelliMains NT controller panel</b>                                                                       |          |      |

### 2.2.2 Transition State to Storage: Discharge

| Step | Description                                                                                                                                              | Feedback | Time |
|------|----------------------------------------------------------------------------------------------------------------------------------------------------------|----------|------|
| 1.   | <b>Plant unit is online and load is approx. 200kW</b>                                                                                                    |          |      |
| 1.1. | Plant is grid tied, with LV incomer 1 breaker open.                                                                                                      |          |      |
| 1.2. | PV plant is online, with PV incomer breaker closed.                                                                                                      |          |      |
| 1.3. | Storage plant is idle with Storage static switch open.                                                                                                   |          |      |
| 1.4  | Diesel genset plant is online with Diesel generator incomer breaker closed.                                                                              |          |      |
| 1.5  | Compressor plant is online and drawing load.                                                                                                             |          |      |
| 2.   | On confirmation by <i>STATION</i> Personnel and the <i>TESTING TEAM</i> that the above conditions are satisfied, the further testing shall be performed. |          |      |
| 3.   | <b>Set storage system to 'Discharge' via HMI operator workstation.</b>                                                                                   |          |      |
| 4.   | <b>HMI closes static switch in battery inverter cabinet.</b>                                                                                             |          |      |
| 5.   | <b>Discharge of 25kW commence.</b>                                                                                                                       |          |      |

### 2.2.3 Transition State to Storage: Idle

| Step | Description                                                                                                                                              | Feedback | Time |
|------|----------------------------------------------------------------------------------------------------------------------------------------------------------|----------|------|
| 1.   | <b>Plant unit is online and load is approx. 200kW</b>                                                                                                    |          |      |
| 1.1. | Plant is grid tied, with LV incomer 1 breaker open.                                                                                                      |          |      |
| 1.2. | PV plant is online, with PV incomer breaker closed.                                                                                                      |          |      |
| 1.3. | Storage plant is discharging with Storage static switch closed.                                                                                          |          |      |
| 1.4. | Diesel genset plant is online with Diesel generator incomer breaker closed.                                                                              |          |      |
| 1.5. | Compressor plant is online and drawing load.                                                                                                             |          |      |
| 2.   | On confirmation by <i>STATION</i> Personnel and the <i>TESTING TEAM</i> that the above conditions are satisfied, the further testing shall be performed. |          |      |
| 3.   | <b>Set storage system to 'Idle' via HMI operator workstation.</b>                                                                                        |          |      |
| 4.   | <b>HMI opens static switch in battery inverter cabinet.</b>                                                                                              |          |      |
| 5.   | <b>Storage system in idle.</b>                                                                                                                           |          |      |

#### 2.2.4 Transition State to PV OFF

| Step | Description                                                                                                                                              | Feedback | Time |
|------|----------------------------------------------------------------------------------------------------------------------------------------------------------|----------|------|
| 1.   | <b>Plant unit is online and load is approx. 200kW</b>                                                                                                    |          |      |
| 1.1. | Plant is grid tied, with LV incomer 1 breaker open.                                                                                                      |          |      |
| 1.2. | PV plant is offline, with PV incomer breaker closed.                                                                                                     |          |      |
| 1.3. | Storage plant is offline with Storage static switch open.                                                                                                |          |      |
| 1.4  | Diesel genset plant is online with Diesel generator incomer breaker closed.                                                                              |          |      |
| 1.5  | Compressor plant is online and drawing load.                                                                                                             |          |      |
| 2.   | On confirmation by <i>STATION</i> Personnel and the <i>TESTING TEAM</i> that the above conditions are satisfied, the further testing shall be performed. |          |      |
| 3.   | <b>Initiate the ‘Open breaker’ command on the IS-NTC-Hybrid controller panel</b>                                                                         |          |      |

### 2.2.5 Transition State to Storage: Discharge

| Step | Description                                                                                                                                              | Feedback | Time |
|------|----------------------------------------------------------------------------------------------------------------------------------------------------------|----------|------|
| 1.   | <b>Plant unit is online and load is approx. 200kW</b>                                                                                                    |          |      |
| 1.1. | Plant is grid tied, with LV incomer 1 breaker open.                                                                                                      |          |      |
| 1.2. | PV plant is online, with PV incomer breaker open.                                                                                                        |          |      |
| 1.3. | Storage plant is idle with Storage static switch open.                                                                                                   |          |      |
| 1.4  | Diesel genset plant is online with Diesel generator incomer breaker closed.                                                                              |          |      |
| 1.5  | Compressor plant is online and drawing load.                                                                                                             |          |      |
| 2.   | On confirmation by <i>STATION</i> Personnel and the <i>TESTING TEAM</i> that the above conditions are satisfied, the further testing shall be performed. |          |      |
| 3.   | <b>Set storage system to 'Discharge' via HMI operator workstation.</b>                                                                                   |          |      |
| 4.   | <b>HMI closes static switch in battery inverter cabinet.</b>                                                                                             |          |      |
| 5.   | <b>Discharge of 25kW commence.</b>                                                                                                                       |          |      |

### 2.2.6 Transition State to Storage: Idle

| Step | Description                                                                                                                                              | Feedback | Time |
|------|----------------------------------------------------------------------------------------------------------------------------------------------------------|----------|------|
| 1.   | <b>Plant unit is online and load is approx. 200kW</b>                                                                                                    |          |      |
| 1.1. | Plant is grid tied, with LV incomer 1 breaker open.                                                                                                      |          |      |
| 1.2. | PV plant is online, with PV incomer breaker open.                                                                                                        |          |      |
| 1.3. | Storage plant is discharging with Storage static switch closed.                                                                                          |          |      |
| 1.4. | Diesel genset plant is online with Diesel generator incomer breaker closed.                                                                              |          |      |
| 1.5. | Compressor plant is online and drawing load.                                                                                                             |          |      |
| 2.   | On confirmation by <i>STATION</i> Personnel and the <i>TESTING TEAM</i> that the above conditions are satisfied, the further testing shall be performed. |          |      |
| 3.   | <b>Set storage system to 'Idle' via HMI operator workstation.</b>                                                                                        |          |      |
| 4.   | <b>HMI opens static switch in battery inverter cabinet.</b>                                                                                              |          |      |
| 5.   | <b>Storage system in idle.</b>                                                                                                                           |          |      |

### 2.2.7 Transition State to Storage: Discharge

| Step | Description                                                                                                                                              | Feedback | Time |
|------|----------------------------------------------------------------------------------------------------------------------------------------------------------|----------|------|
| 1.   | <b>Plant unit is online and load is approx. 200kW</b>                                                                                                    |          |      |
| 1.1. | Plant is grid tied, with LV incomer 1 breaker open.                                                                                                      |          |      |
| 1.2. | PV plant is online, with PV incomer breaker open.                                                                                                        |          |      |
| 1.3. | Storage plant is idle with Storage static switch open.                                                                                                   |          |      |
| 1.4  | Diesel genset plant is online with Diesel generator incomer breaker closed.                                                                              |          |      |
| 1.5  | Compressor plant is online and drawing load.                                                                                                             |          |      |
| 2.   | On confirmation by <i>STATION</i> Personnel and the <i>TESTING TEAM</i> that the above conditions are satisfied, the further testing shall be performed. |          |      |
| 3.   | <b>Set storage system to 'Discharge' via HMI operator workstation.</b>                                                                                   |          |      |
| 4.   | <b>HMI closes static switch in battery inverter cabinet.</b>                                                                                             |          |      |
| 5.   | <b>Discharge of 50kW commence.</b>                                                                                                                       |          |      |

### 2.2.8 Transition State to Storage: Idle

| Step | Description                                                                                                                                              | Feedback | Time |
|------|----------------------------------------------------------------------------------------------------------------------------------------------------------|----------|------|
| 1.   | <b>Plant unit is online and load is approx. 200kW</b>                                                                                                    |          |      |
| 1.1. | Plant is grid tied, with LV incomer 1 breaker open.                                                                                                      |          |      |
| 1.2. | PV plant is online, with PV incomer breaker open.                                                                                                        |          |      |
| 1.3. | Storage plant is discharging with Storage static switch closed.                                                                                          |          |      |
| 1.4. | Diesel genset plant is online with Diesel generator incomer breaker closed.                                                                              |          |      |
| 1.5. | Compressor plant is online and drawing load.                                                                                                             |          |      |
| 2.   | On confirmation by <i>STATION</i> Personnel and the <i>TESTING TEAM</i> that the above conditions are satisfied, the further testing shall be performed. |          |      |
| 3.   | <b>Set storage system to 'Idle' via HMI operator workstation.</b>                                                                                        |          |      |
| 4.   | <b>HMI opens static switch in battery inverter cabinet.</b>                                                                                              |          |      |
| 5.   | <b>Storage system in idle.</b>                                                                                                                           |          |      |

## 2.3 RETURN PLANT TO NORMAL STATE OF OPERATION

### 2.3.1 Transition State to Grid tied Operation

| Step | Description                                                                                                                                              | Feedback | Time |
|------|----------------------------------------------------------------------------------------------------------------------------------------------------------|----------|------|
| 1.   | <b>Plant unit is online and load is approx. 200kW</b>                                                                                                    |          |      |
| 1.1. | Plant is grid tied, with LV incomer 1 breaker open.                                                                                                      |          |      |
| 1.2. | PV plant is online, with PV incomer breaker open.                                                                                                        |          |      |
| 1.3. | Storage plant is idle with Storage static switch open.                                                                                                   |          |      |
| 1.4  | Diesel genset plant is online with Diesel generator incomer breaker closed.                                                                              |          |      |
| 1.5  | Compressor plant is online and drawing load.                                                                                                             |          |      |
| 2.   | On confirmation by <i>STATION</i> Personnel and the <i>TESTING TEAM</i> that the above conditions are satisfied, the further testing shall be performed. |          |      |
| 3.   | <b>Ensure IM-NTC-BB IntelliMains NT controller in manual mode</b>                                                                                        |          |      |
| 4.   | <b>Ensure IG-NTC-BB IntelliGen NT controller in manual mode</b>                                                                                          |          |      |
| 5.   | <b>Initiate the ‘Close breaker’ command on the IntelliMains NT controller panel</b>                                                                      |          |      |

### 2.3.2 Transition State to Diesel OFF

| Step | Description                                                                                                                                              | Feedback | Time |
|------|----------------------------------------------------------------------------------------------------------------------------------------------------------|----------|------|
| 1.   | <b>Plant unit is online and load is approx. 200kW</b>                                                                                                    |          |      |
| 1.1. | Plant is grid tied, with LV incomer 1 breaker closed.                                                                                                    |          |      |
| 1.2. | PV plant is online, with PV incomer breaker open.                                                                                                        |          |      |
| 1.3. | Storage plant is idle with Storage static switch open.                                                                                                   |          |      |
| 1.4  | Diesel genset plant is online with Diesel generator incomer breaker closed.                                                                              |          |      |
| 1.5  | Compressor plant is online and drawing load.                                                                                                             |          |      |
| 2.   | On confirmation by <i>STATION</i> Personnel and the <i>TESTING TEAM</i> that the above conditions are satisfied, the further testing shall be performed. |          |      |
| 3.   | <b>Ensure IM-NTC-BB IntelliMains NT controller in manual mode</b>                                                                                        |          |      |
| 4.   | <b>Ensure IG-NTC-BB IntelliGen NT controller in manual mode</b>                                                                                          |          |      |
| 5.   | <b>Initiate the ‘Open breaker’ command on the IntelliGen NT controller panel</b>                                                                         |          |      |
| 6.   | <b>Place IM-NTC-BB IntelliMains NT controller in auto mode</b>                                                                                           |          |      |
|      | <b>Place IG-NTC-BB IntelliGen NT controller in auto mode</b>                                                                                             |          |      |

### 2.3.3 Transition State to PV ON

| Step | Description                                                                                                                                              | Feedback | Time |
|------|----------------------------------------------------------------------------------------------------------------------------------------------------------|----------|------|
| 1.   | <b>Plant unit is online and load is approx. 200kW</b>                                                                                                    |          |      |
| 1.1. | Plant is grid tied, with LV incomer 1 breaker closed.                                                                                                    |          |      |
| 1.2. | PV plant is offline, with PV incomer breaker open.                                                                                                       |          |      |
| 1.3. | Storage plant is offline with Storage static switch open.                                                                                                |          |      |
| 1.4  | Diesel genset plant is online with Diesel generator incomer breaker closed.                                                                              |          |      |
| 1.5  | Compressor plant is online and drawing load.                                                                                                             |          |      |
| 2.   | On confirmation by <i>STATION</i> Personnel and the <i>TESTING TEAM</i> that the above conditions are satisfied, the further testing shall be performed. |          |      |
| 3.   | <b>Initiate the 'Close breaker' command on the IS-NTC-Hybrid controller panel</b>                                                                        |          |      |

### 3. TEST PROCEDURE ACCORDING TO TIME STAMP

The following section describes the precise time stamp of the various microgrid tests executed on the 8<sup>th</sup> of June 2018.

- 14:45 – Generator synchronization test. Grid tied, PV connected with storage on idle.
- 14:54 – Generator soft load dump and disconnection from grid. Grid tied, PV connected with storage on idle.
- 14:57 – Open storage breaker. Open PV breaker. Grid tied only.
- 14:58 – ESS in autonomous mode. Attempt to discharge with storage breaker open.
- 15:08 – Closing ESS breaker. Grid tied with storage off.
- 15:10 – Starting ESS. Grid tied with storage idle.
- 15:18 – Close PV breaker. Grid tied, PV breaker closed with inverters starting up with storage in idle.
- 15:26 – ESS 50kW charge initiated. Grid tied, PV on.
- 15:32 – ESS set to idle. Grid tied, PV on.
- 15:37 – ESS 50kW discharge initiated. Grid tied, PV on.
- 15:42 – ESS set to idle. Grid tied, PV on.
- 15:43 – ESS 50kW discharge initiated. Grid tied, PV on. (Significant current change set to 60A on storage system connected Vecto II).
- 15:44 – ESS set to idle. Grid tied, PV on.
- 15:57 – Generator start and synchronization to grid. Grid tied, PV on with storage on idle.
- 16:00 – Attempt to start ESS charge with generator connected. Attempt causes ESS to trip.
- 16:01 – ESS 25kW discharge. PV curtailed. Grid tied, PV on, generator connected.
- 16:04 – ESS set to idle. Grid tied, PV on, generator on.
- 16:07 – PV curtailment stops. Grid tied, PV on, generator on with storage on idle.
- 16:11 – Islanding occurs. PV on, generator on with storage in idle.
- 16:14 – ESS 25kW discharge. PV curtailed. Islanded, PV on generator on.
- 16:15 – ESS set to idle. Islanded, PV on, generator on.
- 16:16 – ESS attempt to charge 25kW which causes a ESS trip. Islanded, PV on, generator on.
- 16:20 – Disconnection of PV. Islanded, generator on with storage on idle.
- 16:22 – ESS set to 50kW discharge. Generator curtails. Islanded, generator on.
- 16:23 – ESS set to idle. Islanded, generator on.
- 16:23 – ESS set to 25kW discharge. Islanded, generator on.

- 16:26 – ESS set to idle. Islanded, generator on.
- 16:45-16:46 – Transition to grid tied mode. Grid synchronization. Generator soft load dump and disconnection. PV breaker closed and inverters synchronization. Storage set to idle.
- 16:46 – Tests complete