Grid Integration of Distributed and Renewable Energy Sources: A Network Planning Perspective

Department of Electrical Engineering,

University of Cape Town

Prepared by:

Avinash Ramdhin

Supervisor:

Dr S Chowdhury

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- My managers at Eskom whom have allowed me to progress with my research as part of Eskom's goals in further pursuing IPP integration research.

PLAGIARISM DECLARATION

1. This thesis is my own work.

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TERMS OF REFERENCE

To gain an understanding and know-how of the technical integration of renewable resources into the utility grid and to establish network planning criteria for this integration, the following requirements are listed. These should be met to ensure that an accurate representation of data, results and conclusions can be made based on the completion of the thesis:

- Investigating the current electrical utility grid
- Investigating the processes of Independent power producers (IPP's)
- Investigate and determine methods of technical integration based on current utility assets and design by establishing different integration connection types
- Investigate and determine a manner in which IPP's can connect to the grid technically and filtering the electrical planning components affected by this connection
- Investigating a part High voltage network scenario in which multiple renewable resources may connect to and;
- Investigate the stability of the shared High voltage network during system disturbances and determine a method in which the utility may avoid instability of the High voltage network with concentrated renewable resources sharing common HV infrastructure
- Report the findings of the simulation and tabulate the results
- Make conclusions and recommendations based on the findings
- Provide a technical guideline on the practicality of injecting into the grid with infrastructure requirements and cost thereof
- Provide a correlation of density maps to MW output and assess optimal allocation of renewable energy plants

ABSTRACT

With the drive for cleaner energy, Independent power producers (IPP's) have to find suitable potential land sites that meet their renewable project needs and that prove to be technically feasible to integrate into the nearest distribution electrical infrastructure. Project feasibility for utility grid connection can in certain instances be directed to a specific area due to resource availability and existing electrical plant capability. This invariability leads to multiple establishments of renewable energy plants in the same geographic location. Distribution substations and high voltage (HV) lines in the South African National utility, Eskom, are planned and constructed based on simulation models derived from power system models built in DIgSILENT Powerfactory analysis software. For a Network Planning Engineer, planning for this integration can be become quite complex in a multi-machine scenario as above. This dissertation provides network planning criteria that a planning engineer in the utility can successfully use to plan for this integration. Three sets of criteria are established.

With the inclusion of widespread distributed generation in close proximity of each other, sharing the same grid electrical infrastructure, a critical path of HV electrical elements exists, which the effects of the combined generation control. The first set of planning criteria is derived from the analysis of locating this critical path. This is determined by means of using iterative programming and calculations. Grid voltage stability is one the most important factors in determining the feasibility of generator grid integration. The voltage stability effects of the Eskom Distribution network to which these generating plants connect to, are analysed and tabulated results established. This will enable the utility to determine the location of a specific size of renewable plant, just by knowing the grid strength and not going into detail voltage stability studies. For the second set of planning criteria three sets of network range strengths are identified with corresponding ratios of grid strengths to generator short circuit current contributions. Successfully integrating DG to the grid also has many technical and cost solutions of network configurations. The third set of planning criteria identifies four generic network configurations and the building blocks of physically costing the engineering integration.

Solar density maps provide an indication of proposed MW output in a particular area. In this research, solar density maps are used to identify the maximum connecting generation to the electrical grid in feasible geographic areas. The results derived from this study enable the planning engineer and/or developer to better plan the optimal location of a PV project wrt the chosen geographic area of KZN. This study case may be extended to other technologies leading to a more concise framework of network planning for renewable project integration.

ACRONYMS

AC - Alternating current
AM - Optical air mass
CCT - Critical clearing times
CHP - Combined heat and power
CSP - Concentrated solar power
DC - Direct current
DG - Distributed generator
DFIG - Doubly fed induction generator
DOE - Department of Energy
DNI - Direct normal irradiance
DHI - Diffused horizontal irradiance
DPL - DIgSILENT programming language
GIS - Geographic information systems
GHG - Greenhouse gas emissions
HV - High voltage
kW - Kilowatt
kV - Kilovolt
KZN - Kwazulu Natal
LV - Low voltage
LVRT - Low voltage ride through
MPPT - Maximum power point tracking
MW - Megawatt
MV - Medium voltage
NDP - Network development plan
NREAP - National Renewable Energy Action Plan

PGC - Point of generator connection

PUC - Point of utility connection

PV - Photovoltaic

RVC - Rapid voltage change

ROCOF - Rate of change of frequency

SCIG - Squirrel cage induction generator

SCADA - Supervisory Control and Data Acquisition

Sub - Substation

TSI - Total solar irradiance

VB - Visual Basic

WRIG - Wound rotor induction generator

WTG - Wind turbine generator

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1 Introduction

The significance of this research dissertation is to provide network planning criteria to a planning engineer and the utility in integrating distributed generation into the utility grid. The research studies have determined three sets of criteria for this integration. The first aspect focuses on the penetration levels of distributed generation. The second aspect investigates the stability effects of synchronized generation. The third aspect provides a detailed technical guideline of utility network configuration injection points which includes infrastructure and associated engineering cost estimates.

1.1 Background of the research

Currently in South Africa, renewable energy programs are being designed by the Department of Energy (DOE) for implementation to attract the various technology developments across the country. The drive for the additional capacity that these projects will bring not only assists the utility in supplying the country's electricity demand but enables economic growth expansion. Currently the utility is meeting the consumer's electrical demand but this provides an extremely narrow margin for the utility to complete any maintenance to existing plant, be it power stations or substations. Maintenance is one the key drivers in ensuring adequate quality of supply and maintaining this supply. With staggering electrical infrastructure growth, due to project timelines, extreme capital constraints and skilled resources, having renewable energy sources off-setting electrical load is most essential. Renewable energy program drivers ensure a profitable market to developers. Key targets are set and have to be adhered to, in qualification of becoming a legally connected IPP.

The utility completes a network development plan (NDP) for specific geographic areas throughout the country. Problems and practical solutions are identified, analysed and implemented. These plans cater for long term electrical load growth, by considering; customer trends, type of customers, spatial forecasting, economic trends and refurbishment requirements of existing electrical infrastructure, due to age or capacity constraints. With the proposed widespread geographic location of distributed generation, several questions from a network planning perspective arise. What impact does the injection of additional, non-constant synchronized generation have on the Eskom electrical grid and how does the utility now plan to accommodate this generation from a development plan and operational plan perspective? What conditions are most preferable for these systems to be online? With closely connected generator power stations, how does the utility understand and analyze the penetration of the combined effects of each generator station injecting power at different time intervals? And finally how does the planning engineer assess the technical integration and what guidelines can be used?

The magnitude of generation determines the extent to which the connecting infrastructure is required to be strengthened or refurbished and the voltage level to which the distributed generator (DG) plant may connect to. From a network planning perspective, it is becoming essential that large independent generators of power align their expansion plans to Eskom's Distribution network development plans. This integration will prove to be cost effective and in some cases can reduce the timelines for distributed generator projects to come online.

1.2 Objectives of the research

The aim of this dissertation is to provide technical guidance to a planning engineer and the utility to integrate distributed generation into the network grid. Although various utility guidelines have been recently adopted to assist in the integration [36] [44], *a multi-machine scenario* exists to which the network planning becomes quite complex.

From the point of generator connection to a certain point in an electrical grid, the generator contributes fault current to equipment already rated at a fault level, determined by network configuration (summation of upstream impedance) and design. With multiple generators connected in close proximity, a critical path of components exists to which the cumulative effects of all the generators control. This critical path is defined as the path of interconnected collection of High voltage (HV) equipment, that is or could be adversely affected by the connection of distributed generation, from the point of generator connection to a point in the network to which the combined effects become negligible. In locating this penetration path a planning engineer can easily determine equipment upgrade paths and determine network subsets that prove to be weaker in relation to the entire network grid.

In a multi-machine scenario, steady voltages at all buses are required to be maintained in the system after being subjected to a disturbance from a given initial operating condition. Instability may result in progressive fall or rise of voltages of some buses. If penetration levels becomes higher i.e. a generator affecting a far larger part of a distribution network and possibly the transmission network, distributed generation may start to influence the dynamic behaviour of the power system as a whole [1] [13]. It is not clear as to what criteria a planning engineer can use to determine if a particular network can maintain stability under certain disturbance conditions once the critical path of components are determined.

In assessing the technical integration of a distributed generator, how is this practically connected to the network grid and what network type configurations are most feasible for the generator size? Different network configurations comprising of different network component types and voltages exist. In choosing the most feasible connection type, several factors have to be accounted for.

In addition to technically assessing the integration of distributed generation, the planning engineer in the utility development plans, should include possible land sites that may be feasible to developers in establishing renewable energy projects. This would enable a far better planning practice and cater for future uncertain projects that will have a large impact on load forecasting and network strengthening .

From the above problem statements, the research objectives can be stated as:

1. A method to assist the planning engineer and utility in locating the penetration (critical) path of multiple generators is required to be established.
2. A method to assist the planning engineer and utility to determine the best fit network for connection of multiple generators maintaining voltage stability of proximity busbars is required to be established.
3. A method to practically integrate the generator to the network grid if the generator satisfies both steady state and stability conditions, is required as well as the financial feasibility of such a connection.
4. A study case of selecting best fit land sites and their implication on generation magnitude and grid connection is required to be investigated.

1.3 Scope and limitations

All studies for each of the above stated objectives will be modelled and simulated in DIgSILENT Powerfactory simulation software. The models will be created to be generic in nature but are practical in that in their expansion may form part of a larger network grid. All element data types exist in DIgSILENT and all equipment specifications are industry standards. Each model will be controlled by DIgSILENT Programming Language (DPL) scripts.

All extracted data from DIgSILENT Powerfactory at the completion of each DPL script will be exported to Microsoft Excel for analysis using Visual Basic programming language [30].

Geographic overview pictures will be extracted from ARCGIS software [57]. This software uses shape-files that contain information on the utilities electrical network, land cadastrals, satellite photos, topographical information and various other data layers. The scope of the research for objectives one and two focuses on synchronous machine technology for reasons explained in the next chapter. For the study case solar PV is analysed but may be extended to other technologies which is not covered in this dissertation.

SolarGIS mapping can be found as freeware and is available on the website [51].

1.4 Thesis Outline

The dissertation chapters are structured in the following manner:

Chapter one is **Introduction**

This chapter explains the background and objectives of this research. It also explains the scope required to complete the relevant simulations.

Chapter two is **Literature Review**

This chapter introduces the different renewable energy sources of distributed generation. It then focuses on the nature of Eskom’s networks and the studies that have to be completed in assessing the technical integration of distributed generation. Finally, the chapter ends in discussing the methodology used in this dissertation.

Chapter three is **Case Studies: Design of Simulations**

This chapter presents the designs of the proposed solutions to the objectives stated in chapter one and how each design was planned and executed. Each design is presented in a logical flow and concludes leading to chapter four.

Chapter four is **Results and Discussion**

This chapter presents the results of each design of chapter 3. All results are explained and their relevance and usage to the utility discussed.

Chapter five is **Study Case: Optimal allocation of PV**

This chapter presents a study case of a particular geographic area and uses the studies explained in chapter two to meet objective four of chapter one.

Chapter six **Conclusion, Recommendations and Future Work**

This chapter presents the conclusions derived from chapter four: Results and Discussion. The recommendations and future work is derived from the limitations that were imposed on the constraints of the designs presented in chapter three.

2 Literature Review

This chapter reviews available literature on distribution generation. Different types of renewable energy sources are reviewed but only certain technologies are investigated in this dissertation. From an electrical network planning perspective, the main objective of this research is to provide network planning specific criteria for distributed generation that is integrated into the utility grid.

Section 2.1 provides a description of the different technologies of renewable energy sources and a brief description of cogeneration. Section 2.2 establishes the challenges the electrical utility is exposed to as a result of these technologies being quantified in terms of projects. Eskom, the South African utilities network, is chosen for the studies that follow in the upcoming chapters. The Utilities electrical grid is described and the relevant planning that contributes to the grid structure is also explained and shown diagrammatically. Section 2.4 investigates the impact of penetration levels of distributed generation connected to common electrical infrastructure. Section 2.5 investigates the impact of distributed generation on system stability. Section 2.4 and section 2.5 leads to the establishment of practical methods and critical criteria that is derived and explained further in the thesis. Finally 2.6 discusses the methodology used in each design.

2.1 Cogeneration

Cogeneration, also known as “combined heat and power” (CHP), is the simultaneous production of heat (usually in the form of hot water and/or steam) and power, utilizing one primary fuel [58]. Cogeneration is not a new concept but has been around for many years. Most industries that have the ability to generate power for their own consumption or to export into the electrical grid, do so by utilizing products of their main and current processes.

2.1.1 Types of co-generation plants

Topping cycle plants use steam turbines to produce power and the exhausted heat is utilized for DG district heating [20]. Bottoming cycle plants produces high temperature heat for industrial uses, (DG furnaces) with a waste heat recovery boiler feeding an electrical plant. Some common plant types include gas turbines and gas engines which uses natural gas as fuel, steam turbines, combined cycle power plants and nuclear power plants [20]. Smaller cogeneration plants may use reciprocating engines and some plants utilize biomass (sugar and timber industries) or industrial municipal waste. Some plants may use other alternate sources to compensate for power quality to existing cogeneration facilities, for e.g. solar photovoltaic. Figure 2-1 shows an example of a cogeneration system using a steam turbine [19].

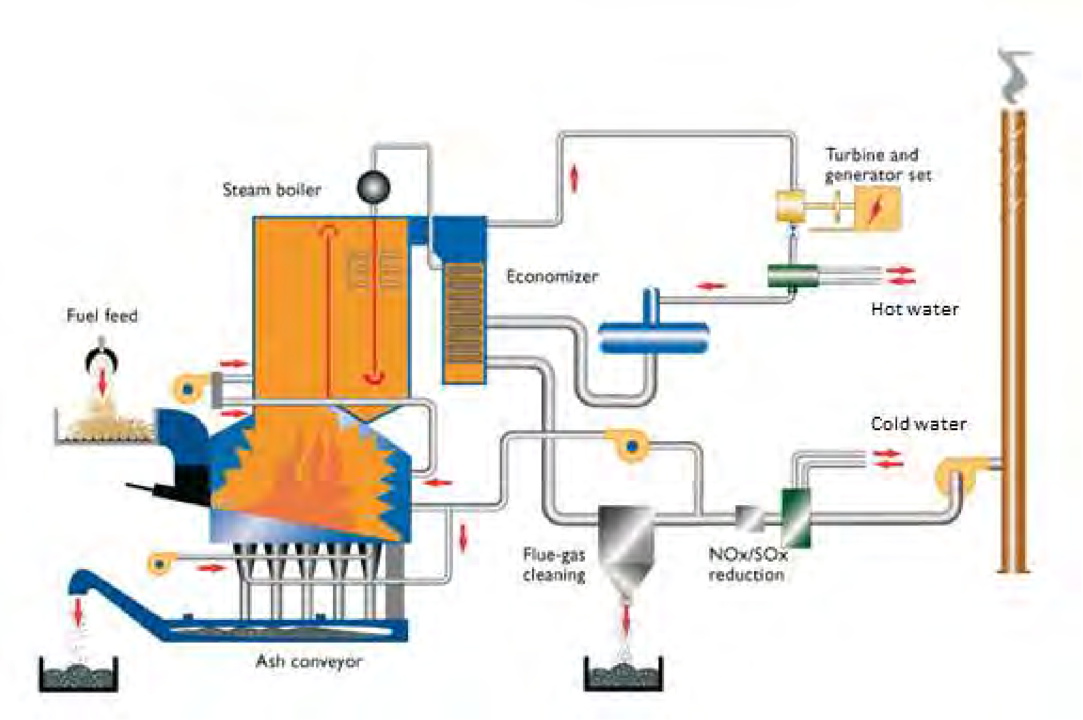


Figure 2-1. Cogeneration plant [19]

2.2 Renewable energy resources

Renewable resources are sources of energy that are continuously being replenished by nature viz. the sun, wind, water, thermal heat from the earth and plants. Renewable technologies transform these natural fuels to other forms of energy such as electricity, and heat. Currently coal, oil and natural gas provide our demand for electricity but these sources will eventually diminish as its utilisation is more rapid than they can be created. These sources of energy are directly harmful to the environment in many ways just by the emissions released in the plant processes and the in mining of the relevant fuel [21].

Greenhouse gas emissions (GHG) have increased the greenhouse effect which is directly proportional to the Earth’s surface temperature. The largest contributor to the rate of climate change is greenhouse gas emissions from the burning of fossil fuels and industrial activity [22].

The increase in these gases has the consequences that rainfall and weather patterns change [22]. Renewable energy sources therefore offers a viable way of reducing the utilization of the above non-renewable energy sources and can be divided into wind power, hydro power, solar power (Photovoltaic (PV) and Concentrated Solar Power (CSP)), geothermal power and bioenergy. Not only does the environment benefit from the use of these natural resources, but in essence the supply to meet the ever growing demand of electricity users is also important. Well configured renewable network injection points may able to reach customers that are well beyond existing electrical infrastructure. The third important benefit is that these injection points may provide redundancy within the existing networks. A few commonly used renewable sources viz. wind, solar, CSP and bioenergy technologies are discussed further.

2.2.1 Wind Power

Wind turbine generators (WTGs) transform energy from wind into electricity via an aerodynamic rotor, which is connected by a transmission system to an electric generator. A power transformer integrates the WTG energy into the grid [23].

Wind turbine speed ranges from 3m/s to a maximum of 13m/s. Typically power output is directly proportional to the rotor swept area where a 10% increase in wind speed increases available energy by 33% [23]. The mechanical structure of a wind turbine is shown in figure 2-2.

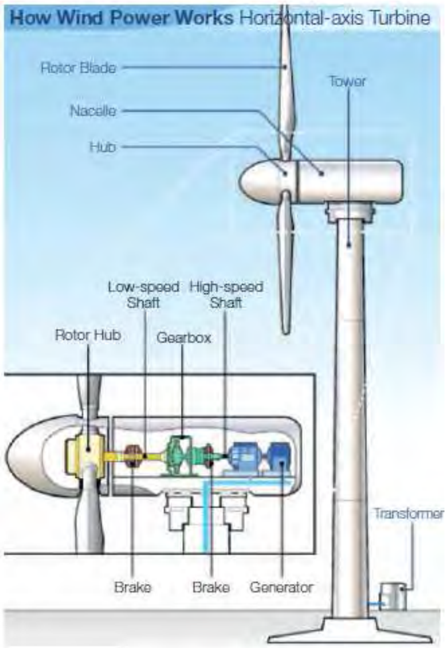


Figure 2-2. WTG structure [23]

Power output can be controlled to adapt to wind direction and strength by:

- rotating the nacelle horizontally (yawing) and,
- rotating the turbine blades around their long axes (pitching).

A wind farm consists of many WTGs connected together as shown in figure 2-3. The interconnection may be cable or overhead. An example of a single line diagram of a wind farm is also shown in figure 2-4 [24].

Figure 2-3. Example of a large wind farm [59]

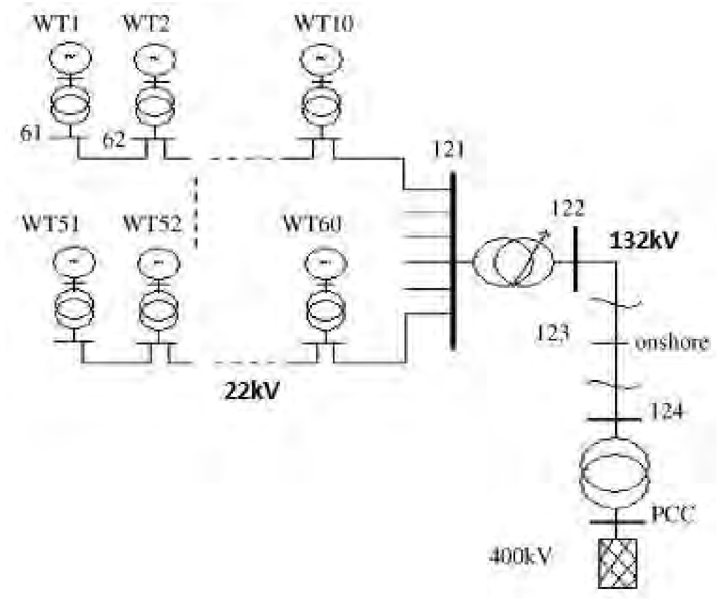


Figure 2-4. Example of an electrical single-line diagram for a wind farm [24}

2.2.1.1 Types and characteristics of major WTGs

There are four types of WTG's:

A. **Type 1 – Fixed speed induction generator (SCIG):**

Type 1 WTG's are based on a squirrel cage induction generator (SCIG). Turbine speed is almost fixed to the electrical grid frequency and generates when a negative slip is created (shaft speed exceeds grid frequency). Because induction generators absorb a lot of reactive power when generating active power, type 1 generators are usually equipped with reactive power compensators [25].

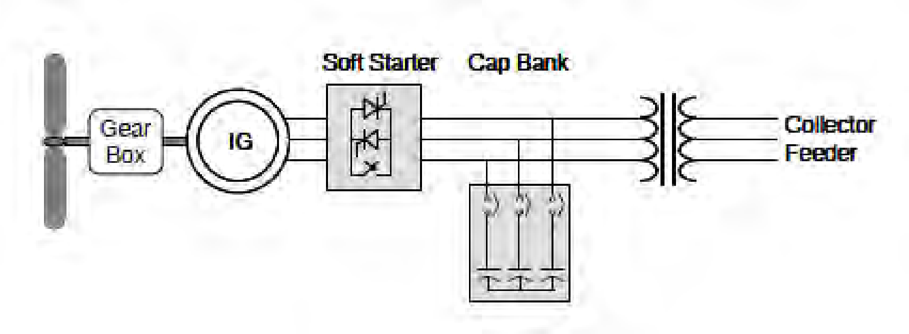


Figure 2-5. Type 1 SCI [25]

B. **Type 2 – Variable-slip induction generator (WRIG):**

Type 2 is similar to type 1 with regards to the machines stator circuit, but is equipped with a variable resistor in the wound rotor circuit. Power electronics control the quantity of the rotor current reducing the mechanical loading of the turbine components. Speed variations of up to 10% are possible.

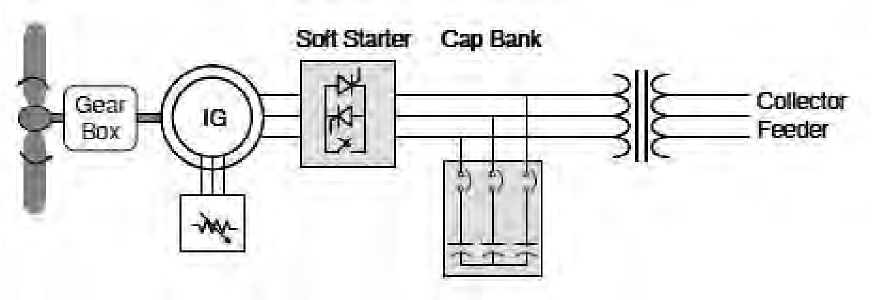


Figure 2-6. Type 2 WRIG [25]

C. Type 3 – Doubly fed induction generator (DFIG):

DFIG wind turbines combine the designs of type 1 and type 2 with advances in power electronics. Variable frequency ac excitation is now added to the rotor circuit. The rotor's current magnitude and phase can be adjusted almost instantaneously. A small current injected into the rotor circuit can affect a large control of power in the stator circuit. The converter provides decoupled control of active and reactive power, enabling flexible voltage control without additional reactive power compensation. Fast voltage recovery and voltage ride-through is also enabled.

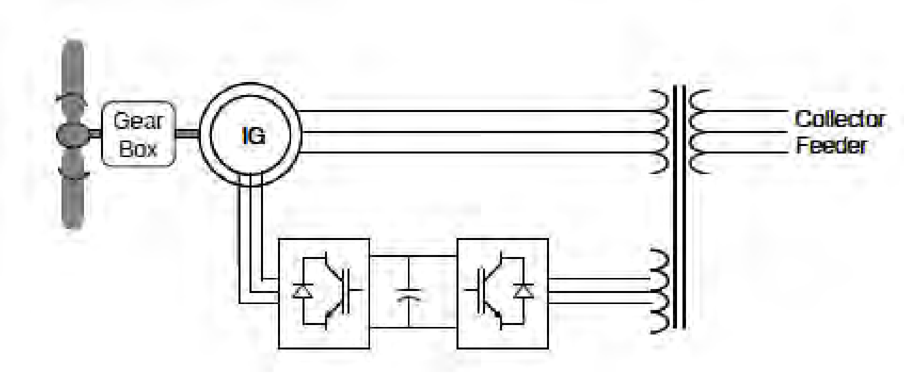


Figure 2-7. Type 3 DFIG [25]

D. Type 4 – Full-power conversion WTG:

In a type 4 wind turbine generator, the stator of the generator is connected to the grid via a full-scale back-to-back frequency converter, which means all the power output goes to the electrical grid through the converter as shown in figure 2-8. The generator may be a synchronous generator with wound rotors, a permanent magnet generator or a SCIG. Similar to the characteristic of the type 3 wind generator, a type 4 generator can provide a much greater range of speed variation as well as reactive power and voltage control capability. Its output current can be adjusted to zero, hence limiting the short-circuit current contribution to the grid [25].

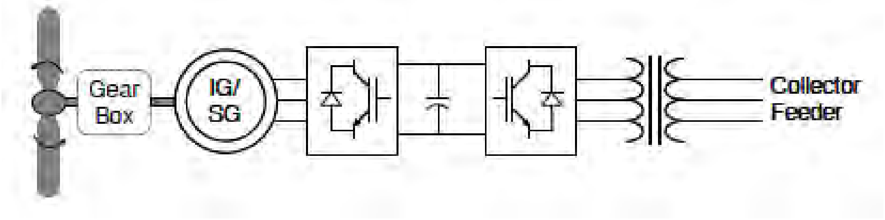


Figure 2-8. Type 4 full power [25]

2.2.2 Solar Radiation and PV Power

Solar radiation refers to electromagnetic radiation emitted by the sun. The total amount of solar radiation received at normal incidence at the top of the earth's atmosphere, at the mean sun-earth distance, is defined as the *Total Solar Irradiance* (TSI) [31] [32]. TSI is given the term 'solar constant' and is approximately 1367Wm^{-2}.

A. Components of Solar Radiation

A *direct* component (DNI-direct normal irradiance) of sunlight is that part that directly reaches the earth's surface. Scattering of sunlight in the atmosphere generates the diffuse component (DHI-diffused horizontal irradiance). The reflection of solar radiation by the earth's surface is called *albedo* and may be part of the total solar radiation (global solar radiation) [31] [32]. Distance between the earth and sun is the most important parameter that determines the magnitude of solar irradiance. This distance is at its shortest when the sun is at its *zenith*, i.e. directly overhead. The ratio of an optical path length to the zenith is referred to as the *optical air mass (AM)* [31] [32]. When the sun is at the zenith, *AM* is unity (*AM1*) and at any angle is defined as:

$$\text{Air mass} = (\cos\theta)^{-1} \tag{2-1}$$

Global solar irradiance, wrt a horizontal surface is the sum of the vertical component of the DNI component and the DHI component [31].

$$\text{Global Solar Irradiance} = \text{DNI}.\cos\theta_2 + \text{DHI} \tag{2-2}$$

where θ_2 is the angle between the direct beam and normal to the surface.

Figure 2-9 below illustrates the three components of solar irradiance.

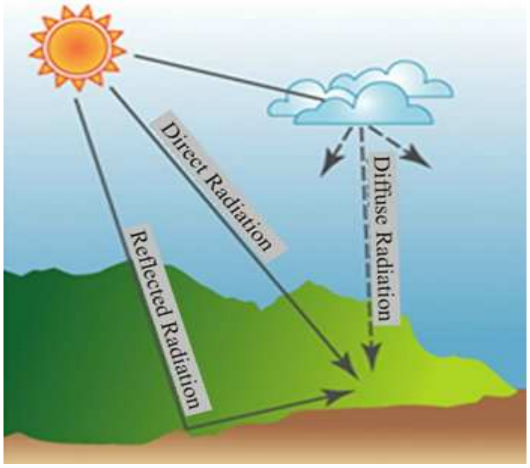


Figure 2-9. Components of solar irradiance [60]

2.2.2.1 Types and characteristics of PV

There are three current PV technologies viz. crystalline silicon, thin film and concentrating PV. Crystalline silicon PV is currently the best established PV technology, with an energy conversion efficiency of up to 20%.

Photovoltaic cells convert the solar irradiance into electricity similar to the effects of the functioning of the P-N junction diode [53]. Figure 2-10 shows the basic construction of the PV cell. Several PV cells make up a module and several modules make up an array as in figure 2-11. Figure 2-12 shows the electrical block diagram of connecting PV arrays to the utility grid.

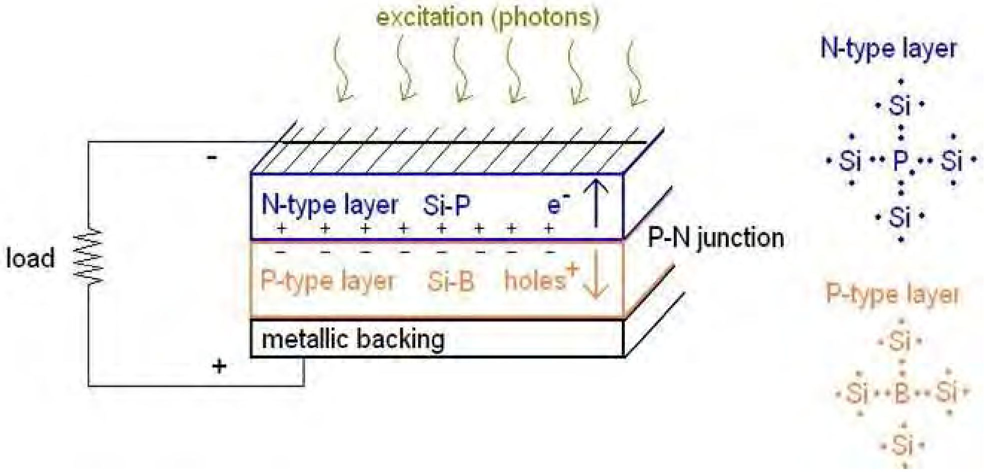


Figure 2-10. Construction of a solar cell [62]

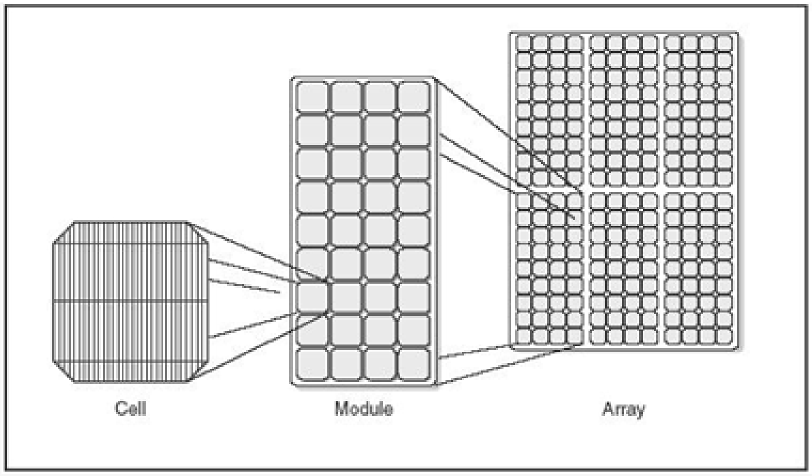


Figure 2-11. Cell to Array formulation [61]

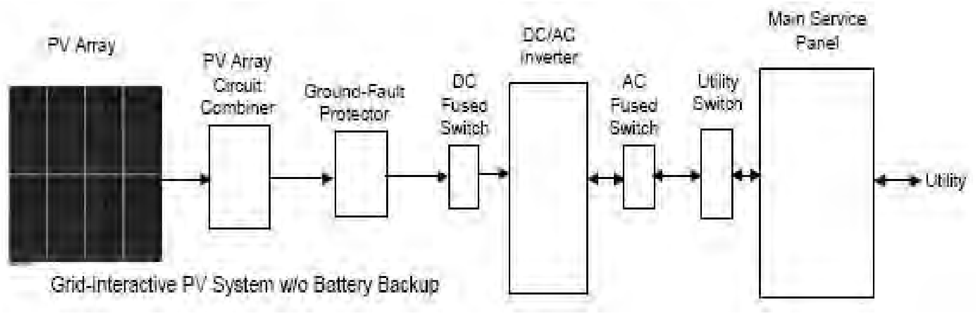


Figure 2-12. Electrical schematic of interconnecting components [14]

2.2.2.2. Factors affecting PV module outputs:

- *Temperature:* Output power reduces as module temperature increases. A PV cell performance parameters, viz. open-circuit voltage, short circuit current, curve factor and efficiency, are temperature dependent [33].
- *Dirt and Dust (Soiling):* Accumulation would block sunlight reducing outputs. Losses are generally 1% if not adequately cleaned [34].
- *Mismatch and wiring:* The total output of a PV plant is always much less than the maximum output of individual arrays. A reduction factor of 0.95 is typically used. The inconsistency of each module performance is the mismatch and can amount to 2% of loss in system power.
- *DC to AC conversion losses:* The DC power generated is converted by AC converters with a typical efficiency of 90% [34].
- *Maximum Power Point Tracking (MPPT):* The power output of a PV module changes with sun direction, irradiance level and as mentioned varying temperature [34]. A single peak power point exists corresponding to a specific voltage and current. A MPPT is used for extracting the maximum power from the solar module and transferring that power to the load [34], which significantly increases power plant output.
- *Islanding with inverters*: As stated in [6], that under islanding conditions, no distributed generator is allowed to supply an islanded network. For PV installations, grid-tied inverters monitor the utility line voltage and frequency continuously [35]. Most inverters have low voltage ride through (LVRT) and flexible active and reactive power control capabilities but those that do not shut themselves off quickly under abnormal voltage or frequency conditions. Unintentional islanding with inverters is very difficult to sustain because the inverter is not designed to regulate output voltage [35].

- *Solar irradiance and power output*: The conclusions derived in [33] from measured and simulated comparisons show that maximum power produced decreases by approximately 30% when solar irradiance decreases from 1000W/m^2 to 700W/m^2 and decreases by a further 31% with a drop of another 300w/m^2. In concentrated PV, sunlight is concentrated and strengthened by a lens before it reaches the PV cells and can reach an efficiency of up to 40%.

The efficiency of a PV installation can also be attributed by % losses as below (depending on site, technology, and sizing of the system) [34]:

- Inverter losses (6% to 15 %)
- Temperature losses (5% to 15%)
- DC cables losses (1 to 3%)
- AC cables losses (1 to 3%)
- Shadings - 0% to 40% (depends on site)
- Losses weak irradiation 3% to 7%
- Losses due to dust, snow... (1%-2%)
- Other Losses which include the connecting grid

Sunlight density is more predictable than wind; however the relatively high cost of setting up PV power plants has being a disadvantage wrt the rate of establishment of wind energy facilities.

2.2.3 Concentrated Solar Power (CSP)

CSP generation is also known as solar thermal power generation [23]. CSP plants produce electric power by converting the sun’s energy into high-temperature heat using various mirror configurations. The heat is then transmitted to a conventional generator driven by a steam turbine, gas turbine or heat engine where this thermal energy is then converted into electricity. CSP plants may also be equipped with thermal energy storage systems for operating during cloudy periods or at night [26] [23]. A CSP plant can be stabilized by utilizing fossil fuel to supplement the output during periods of low solar radiation.

2.2.3.1 Types and characteristics of CSP

Four types of CSP technologies are used [26]:

- *Parabolic trough systems* use long rows of parabolic mirrors to reflect and concentrate sunlight radiation onto a linear receiver pipe that contains the relevant fluids. . Power output is in the MW range.

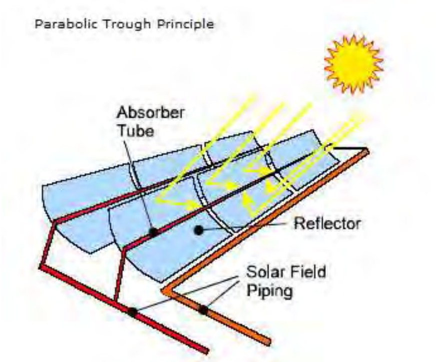


Figure 2-13. Parabolic trough system [26]

- *Linear Fresnel reflector systems* use long rows of flat or slightly curved mirrors to concentrate the solar radiation onto a downward-facing linear receiver tube situated in the space above the mirrors. Power output is in the MW range.

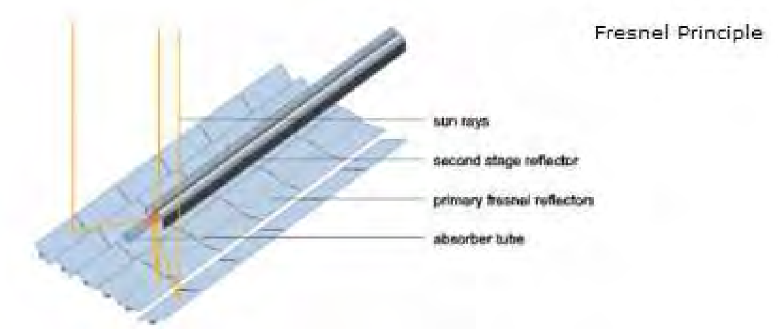


Figure 2-14. Linear Fresnel reflector system [26]

- *Solar tower systems*, called power tower systems use numerous large, sun-tracking flat mirrors (heliostats) to concentrate solar radiation onto a receiver situated at the top of a tower. Power output is in the MW range.

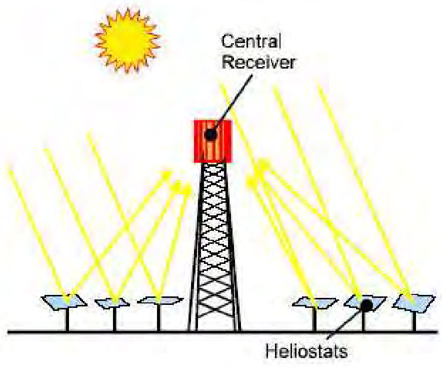


Figure 2-15. Solar tower system [26]

- *Parabolic dish systems,* also known as dish/engine systems, concentrate solar radiation onto the focal point of a single reflective dish, where the receiver and an engine/generator (such as a Stirling machine) are installed. The collected heat is directly used by this heat engine and moves with the dish structure. Power output is only in the 10kW range.

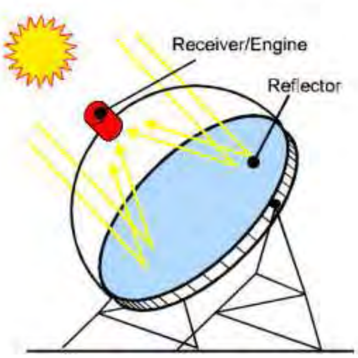


Figure 2-16. Solar tower system [26]

CSP can provide a stable grid with a hybrid system design and offers heat storage capability. This is ideal to a utility in that this energy can be dispatched during peak times when the power is actually required to offset existing utility supply. However, the technology to use CSP has not matured and the installation of CSP plants is not cost effective. Also, the location to optimize the effectiveness of the plant is limited to extreme temperature regions. In addition, water is required for cooling which is not easily accessible in dry, hot regions and other dry cooling methods is also not cost effective.

2.3 Challenges integrating Distributed generation (DG) into the utility grid

The different types and characteristics of distributed generation were discussed in the previous sections of this chapter. With the growing market of providing system components to these DG types, make the DG plant in its entirety to a developer a profit making investment. These components e.g. solar panels are starting to become locally manufactured. With the reduction in import costs, local job creation and favourable technical and environmental factors enable all relevant National support to drive the establishment of DG.

The frequent challenge that a utility is faced with is providing a stable and robust power system in planning for electrical growth, be it load or generation. In ensuring acceptable levels of the quality of supply of the power system [5], the utility maintains, refurbishes and strengthens existing electrical infrastructure and equipment and ensures that all regulatory measures and policies are strictly adhered to. These regulations are explicitly defined and outlined in the various Distribution and Transmission network and grid codes [5]. Electrical growth is derived from economic growth and has many triggers and types.

The utility develops network plans that align with this load growth and forecasts this growth over a many year period (typically 10 years). This plan details what electrical network strengthening or refurbishing of network infrastructure is required. The implementation of these development plans for the refurbishment or establishment of new infrastructure, has tremendously staggered due to project timelines, extreme capital constraints and the lack of various skilled resources. The gap between forecasting load growth and actual project implementation has drastically widened. The consequence is that basic electricity demand will quickly start exceeding supply. Not only does renewable energy resources reduce the risk of damage to the environment but technically offers alternate injection point sources that could bridge the above gap and defer if possible certain capital projects that were derived from the network plans.

From an electrical network planning perspective, the implications of having distributed generation, synchronizing and injecting into the electricity grid, has many technical implications, especially if different renewable stations connect to a common network, high or medium voltage. The essence of this research is therefore to find technical guidance in utility network planning for this multi-machine integration. In order to establish this guidance, the technical nature of the utility network has to first be understood.

2.3.1 Existing South African utility network structure

The current Eskom electrical system comprises of various substation and line network configurations. It is difficult at an instance to determine the interconnecting infrastructure required to allow the technical compatibility of a distributed generator to the utility grid. The network description given in this section is limited to the Kwazulu Natal area of South Africa.

Eskom’s Distribution high voltage (HV) system in KZN consists of two voltages, 88kV and 132kV (defined as sub-transmission voltages). The 132kV is supported by strong Transmission (>132kV) sources and is therefore quite robust and the proposed voltage system to connect to. The 88kV system feeds mostly traction loads and may not be as strong as the 132kV system as a large generator connecting voltage.

Figure 2-17 shows an example of an existing HV network with 88kV and 132kV distributed in the KZN area. Having such a network entrenched within the density shown in figure 2-17 leads to many issues that affect the network on a technical basis. Assuming that additional capacity is required, one such issue would be the availability of servitudes for additional lines and substations. These lines or substations may be network strengthening injections to the existing grid but the facilitation of these projects may be greatly affected by the environmental framework, cost and constructability hence making the access to much needed servitudes difficult. These lines are the infeeds to various voltage type substations. Substations (S/S) are the transformation stations from high voltage to medium voltage that are required at the relevant load centres. Medium voltage (MV) consists of voltages less than 33kV but limited to 1000V. Voltages that are less than or equal to 1000V are defined as low voltage (LV).

The utility builds, maintains and monitors all Transmission and Distribution electrical networks within the country and within the Distribution legal area of supply [5]. Almost every network is modelled for redundancy and additional load, via various power system tools and is operationally monitored via a Supervisory Control and Data Acquisition (SCADA) system at the relevant control centres, once they are commissioned.

Figure 2-17. Geographic overview of 88kV and 132kV networks meshed in the KZN area [57]

2.3.2 Network strengthening and development planning

When Eskom undertakes capital projects to cater for increasing electrical load, refurbishment of existing networks or strengthening the electrical infrastructure in specific areas (as in figure 2-17), several factors in the area analysis has to be accounted for.

A network development plan (NDP) is completed for that specific area in which problems and practical solutions need to be identified, analysed and implemented. These plans cater for long term electrical load growth, by considering; customer trends, type of customers, spatial forecasting, economic trends and refurbishment requirements of existing electrical infrastructure, due to age or capacity constraints.

Using DIgSILENT Powerfactory (load flow analysis software) [30], a simulation model is created for all electrical options identified. The technical analysis motivates and finalizes the solutions that are eventually approved by various technical approval forums and documented in the NDP. Fixed criteria, derived from grid and network standards and specifications [45] [46] result in satisfactory modelling of a network planning solution and the initiation of Eskom capital projects. Examples of such criteria are line and transformer loading thresholds, fault level withstand capability ratings, fault current injection impacts, voltage regulation limits [5] and network re-configuration.

Figure 2-18 is an extract of a development plan showing a load forecast (Sub 1 and sub 2 stations) and new additional infrastructure that is required to be added on to the network.

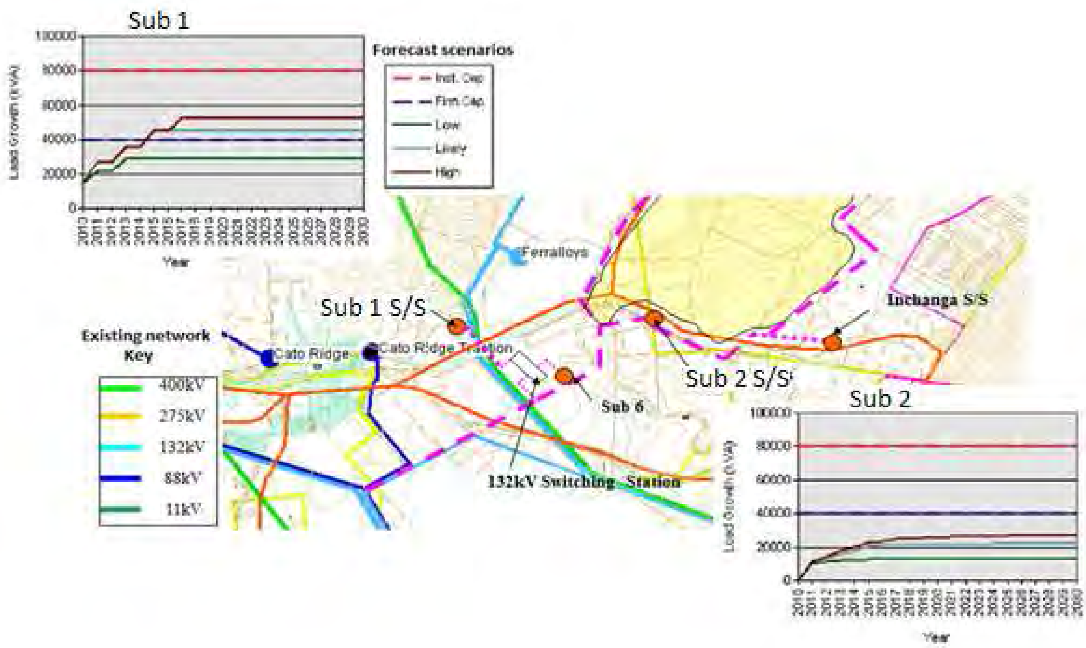


Figure 2-18. Development plan abstract [63]

Figure 2-19 shows an extract of the simulation model defining the technical criteria at a particular point.

Different countries have approached renewable energy plans in different ways. National Renewable Energy Action Plans (NREAP) was required to be adopted by all states in Europe. This plan set out sectorial targets and measures to achieve targets set by the directive of the European commission on the promotion of energy usage from renewable energy sources [55]. Most of the NREAPs indicated no reduction in energy consumption by 2020 but an increase. Specifically, biofuels in the NREAPs are planned to be more than doubled. It is quite evident from the technical assessment of all the NREAPs that biomass is chosen as the renewable energy source to achieve their National targets [55].

In Australia, the city of Sydney has created a renewable energy masterplan [56]. This plan identifies the best fit practice of integration to the grid and explains the policies that enable this integration. The master plan has targeted high energy demand loads. The zones identified as low carbon infrastructure zones will be supplied by a new thermal energy network using waste heat from local electricity generation [56]. This method reduces peak loads and the need for network upgrades.

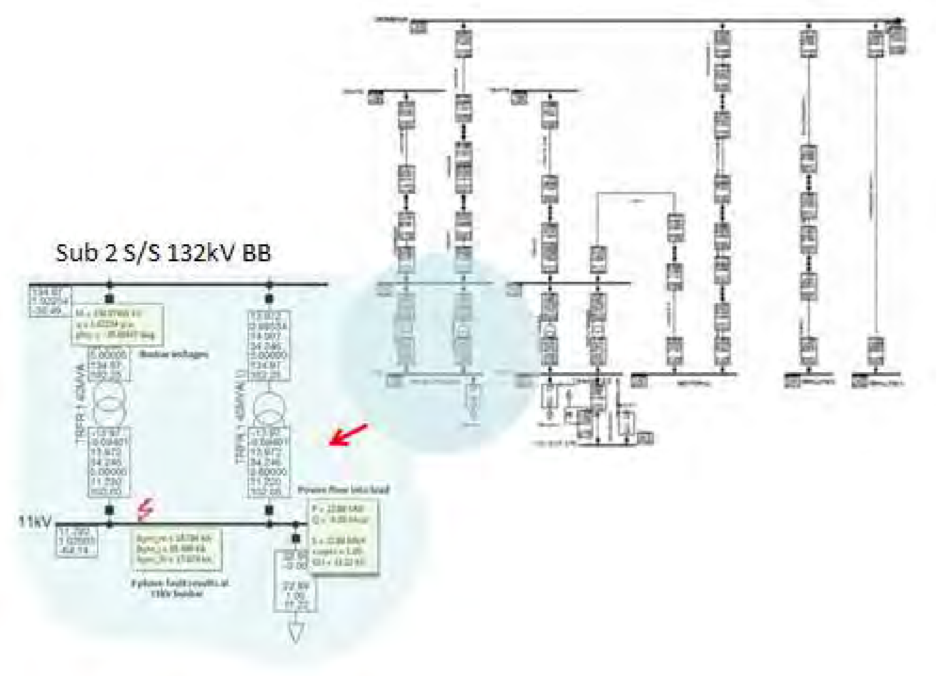


Figure 2-19. Model of new network to the existing network [30] [63]

2.3.3 Distributed generation integration in South Africa

Specific resources (such as fuel sources) in areas, make the location of a generating plant feasible (quantity, quality, transportation costs etc.), however this is also directly controlled by plant establishment cost factors and the integration of the electrical part of the plant to the utility grid. This may pose a problem in terms of the electrical network planning requirements for that specific area. The typical network scenario is that the utility has been continuously planning, designing and constructing electrical infrastructure to service rural, urban, commercial and industrial loads for forward power flow. In addition, from a protection philosophy perspective, problems arise with reverse power flow. Several questions compliment the possible problems that could arise:

- Is the current electrical protection adequate to cater for this?
- What steady state criteria should be met for this integration?
- What would transpire on the advent of instability events?
- Would the utility need to spend more capital on electrical infrastructure than needed to accommodate new renewable plants or more distributed generation?
- Would this cost then make the generating plant project itself not feasible, considering that the additional cost is directed to the developer/customer?
- How does the utility fit the renewable plant into their development plans?

Figure 2-20 shows an example of a geographic overview of proposed projects that may be connected to the utility grid. This geographic location is not as meshed as in figure 2-17 which therefore limits the interconnecting points; however, figure 2-20 clearly gives insight to the scenario that may arise. Multiple renewable generating plants may find common resources (e.g. adequate wind or high irradiance for PV) or feasible geographic locations that may improve their own plant efficiencies. With such closely connected generator power stations, how does the utility understand and analyse the penetration of the combined effects of each generator station injecting power at different time intervals?

Steady state analysis of distributed generation provides a first pass technical integration approval of connection and if this analysis poses no technical constraints w.r.t. acceptable thermal limits of conductors, acceptable voltage regulation at relevant busbars, acceptable fault levels at relevant network points and within limits of rapid voltage change tests of relevant busbars [36], would the system still be consistently stable under certain conditions? And if so what conditions define this? What is the probability that all of the proposed new plants are commissioned as per their respective timelines but misalign with utility strengthening project timelines?

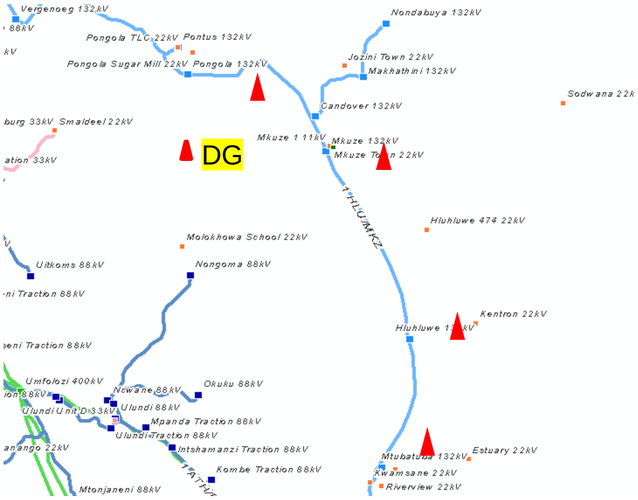


Figure 2-20. Geographic overview of an example of widespread DG units [57]

From a network planning perspective, it is becoming essential that large independent generators of power align their expansion plans to Eskom's Distribution network development plans. This integration proves to be cost effective and in some cases reduces the timelines for distributed generator projects to be grid tied.

Issues associated with the operation of the above integrated system include safety, voltage profiles, power quality, reliability, protection, unbalance/asymmetry, stray voltages and currents, and electromagnetic compatibility issues [16].

Applying scenario-based grid planning offers possibilities of developing network grids in proactive ways. With the various scenarios, future bottlenecks can be identified early on in the planning stage. When generated power exceeds the load of a distribution feed, voltage rise will occur. This voltage rise caused by the reversed power flow is a function of the power generated by the DG and the short-circuit power of the grid at the point of interconnection.

An operational approach can then be to constrain the DG unit at times of low demand and so expensive grid reinforcements can be prevented. This can be an attractive option when the DG unit is dispatched. DG units including synchronous machines can absorb some reactive power and in this way can help reduce voltage rise. However, controlling voltage level by controlling the reactive power flow only works for distribution feeders with sufficient X/R ratio. X/R ratio is the ratio of reactance to resistance in the feeder supply. The voltage rise is a steady effect and strongly depends on the X/R ratio, feeder load and DG injected power. The DG can also have a transient effect on the voltage level. A rapid load current variation of a

DG unit causes a sudden increase or decrease of the feeder current and hence an effect on the feeder voltage. This is discussed in the next section.

Two sets of studies as mentioned above are identified to completely assess the technical integration of distributed generation to the utility grid, viz. Steady state studies and transient stability studies. These are now explained in section 2.4 and 2.5.

2.4 Distributed generation integration effects: Steady state analysis

Steady state studies involve calculating short circuit current contributions from the generator to the grid, calculating the resultant voltage and instantaneous change in voltage upon connection of the generator to the grid both during peak and off-peak times of maximum and minimum generation [36]. Load peak times are typically when the demand on the power system is the greatest and for off-peak the load is at its minimum. These aspects are discussed in the sections that follow.

2.4.1 Generator fault current injection

The main factor that drives this current is derived from the machine’s impedance parameter, the subtransient reactance (Xd"). Xd" is the positive-sequence impedance that determines the three-phase fault current during the first few cycles. Typically, Xd" is between 10-30% of the machine rating. Higher values of Xd" limit the short-circuit current that the machine supplies but reduces the capability of the machine to respond quickly to load changes [3]. Figure 2-21 shows two graphs of Xd" (0.1 & 0.2p.u) and the current that is supplied under a fault condition for three different voltages (6.6kV, 11kV & 22kV).

Typically fault level mitigation is the responsibility of the DG developer [2], however, in some cases with the plant having fault ride through capability, all new lines and connecting equipment must be adequately rated to be within 10-20% of the sum of the network fault level and machine fault level injection. Some of the options that a developer would have to limit fault current [4, 7]:

2.4.1.1 Upgrade equipment: If possible. Use high impedance transformers. This is the most expensive option.

2.4.2.2 Install series reactors: Increases network losses. Relatively high cost but can be maintained.

2.4.2.3 Install IS limiters [8]: New technology. This has a relatively high cost of component replacement.

2.4.3.4 Create normally open points. This is relatively low cost but there are limits on practical implementation.

From the point of generator connection to a certain point *X* in an electrical grid, the generator contributes fault current to equipment already rated at a fault level, determined by network configuration (summation of upstream impedance) and design. With many distributed generators connected in close proximity, a critical path of components exists to which effects of the combined generation control [6]. The critical path is therefore defined as the path of interconnected collection of HV equipment, that is or could be adversely affected by the connection of distributed generation, from the point of generator connection to a point in the network to which the combined effects become negligible. The significance of this critical path is that part of the utility network is identified, which is affected by generator fault current under a short circuit condition. All network equipment is limited in its construction and withstand capability by a short circuit current rating, so identifying the HV components in this path enables the prioritization and financial investment of strengthening and/or refurbishing projects.

The fault current contribution of a PV installation is typically 1.2 times the power rating [44] [5].

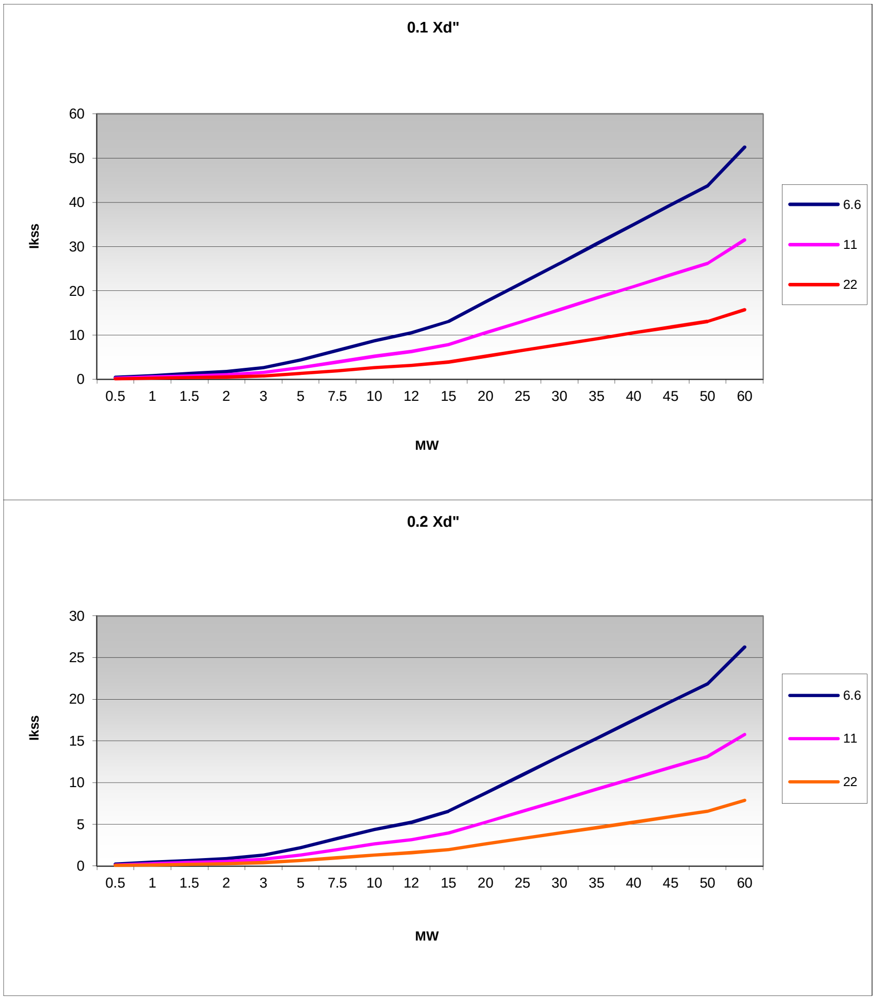


Figure 2-21. Graphs showing the comparison of Xd”

2.4.2 Voltage rise

Distributed generators normally follow the utility voltage and inject a constant amount of real and reactive power. However, distributed generators can cause voltages outside the regulation standards. High voltages are caused by the injection of real power upstream into the system, leading to voltage rise [6, 9]. Distributed generators raise voltage mostly where X/R ratios are low**.** The real power portion causes the largest voltage rise when the line resistance is high [9]. If the generator injects reactive power (VARS), the voltage rise is even worse.

For all networks, voltage regulation is controlled with the limitations set out in NRS048-4:2009: Quality of supply regulatory standards [39]. Voltage rise on weak medium and low voltage networks is a major limiting factor.

For an MV feeder (in the Eskom utility network), the sending voltage is typically set at 1.03 per unit (p.u) at the MV feeder substation. Ideally all distribution network customers' should have their MV to LV transformers tapped according to the Eskom Voltage Apportionment limits standard [6].The standard dictates what tap the MV/LV transformer needs to be set at such that at peak and off-peak conditions; the correct voltage regulation on the network feeder is maintained which directly influences the quality of supply on the MV and LV network. The operating mode of small generators is usually to run as power factor controlled mode.

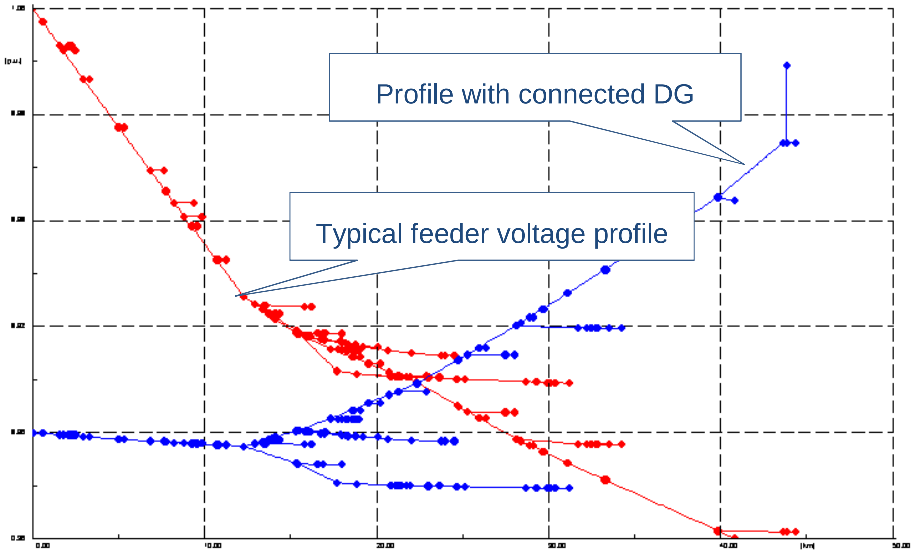


Figure 2-22. Voltage profiles on medium voltage networks

2.4.3 Rapid Voltage Change (RVC):

A rapid voltage change in the RMS value of a voltage signal that moves from a steady state value to a maximum change, gradually varies and then settles at a new steady state voltage [12]. It is characterized by the variables shown in figure 2-23 below. The RVC value defined in [44] is that for fluctuating generation such as solar or wind, is less than 3% and for non-fluctuating generation such as biomass, biogas etc. is 5%.

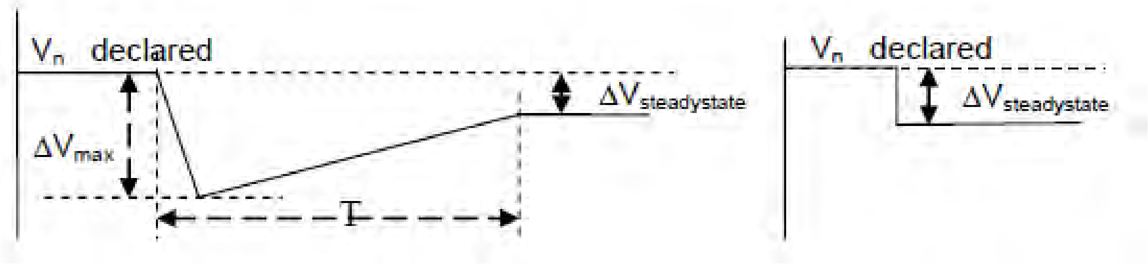


Figure 2-23. Characterization of rapid voltage change [12]

2.4.4 Line types and capacity

Figure 2-24 shows the current carrying capacity of several High voltage (>=33kV) and medium voltage (<33kV) lines used in Eskom Distribution. The templating temperature determines the maximum current that the line can withstand under normal operating conditions [45].

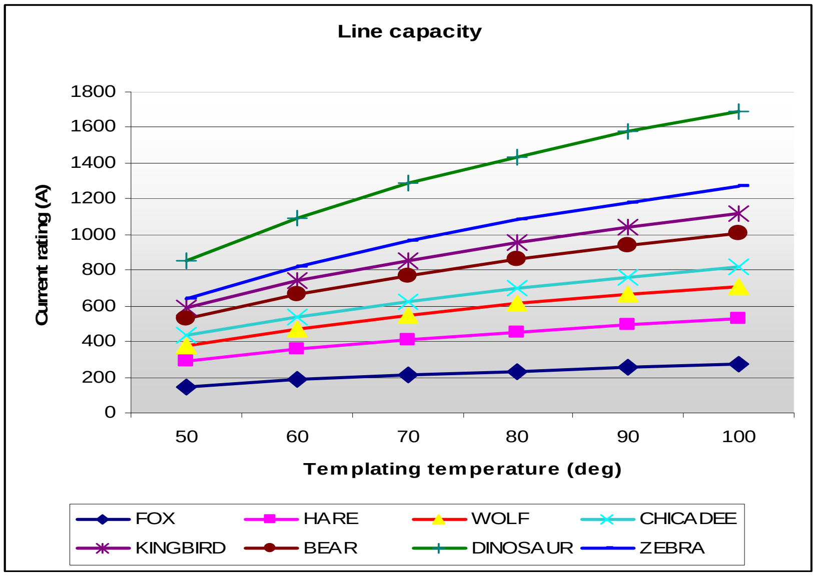


Figure 2-24. Line type specifications [45]

This temperature design criterion ensures adequate ground clearance of the conductor when strung on towers and pole structures to be within set safety regulations [54]. As the temperature increases due to power flow, conductors tend to sag and can compromise safety if not properly designed. To mitigate existing lines that have this problem, structures are inserted between existing poles or towers to maintain the sag clearance from ground. Older built lines were designed using the 50° standard but newly designed lines are built at typically 75° standard which implies a 40-50% increase in carrying capacity.

With the connection of a generator to an existing line as above (depending on network configuration) the maximum current carrying capacity of the line is determined to be able to carry the maximum generated power (in the case of multiple units, it would be the sum) during light loaded conditions [5]. For example at 70°, the conductor Hare carries 400A. Now at a voltage of 22kV, the power carrying capability of the line would be 15.2MVA but depending on voltage rise and RVC studies, the allowable generation will be much less than 15.2MVA. Every line is also rated at a fault current specification (kA value) much greater than network fault level at that point which is determined by normal network configuration and upstream network impedance.

2.4.5 Codes and policies

In the South African Distribution Network Code, it is stipulated that a distributor must have an interconnection standard specifying the technical criteria for the connection of a distributed generator to the electrical grid [5]. The Eskom Distribution Standard (DST 34-1765) specifies the minimum protection requirements that a distributed generator needs to adhere to for connection to the utility grid [6]. Table 2-1 shows the protection requirements at the point of grid connection [6]. As mentioned previously, the NERSA distribution grid code stipulates the network criteria that the utility must adhere to when operating and designing networks [5]. These regulations also apply to distributed connected generation as well.

Table 2-1. Protection requirements: DST 34-1765 [6]

Protection Type	HV	MV
Overcurrent, Earth Fault	Yes	Yes
Sensitive Earth Fault (SEF)	No	Note 1
Phase Under/Over Voltage	Yes	Yes
Residual Over-Voltage	No	Note 1
Under/Over Frequency	Yes	Yes
Loss-of-Grid	Yes	Yes
Check Synchronising	Yes	Yes
Reverse Power	Note 2	Note 2
DC Failure Monitoring	Yes	Yes
Note 1: Dependant on Neutral earthing philosophy adopted Note 2: Only if no power is to be exported to the grid		

2.5 Distributed generation effects: System stability

If grid integration of distributed generators fulfils the acceptable criteria defined for steady state analysis, then the next area of concern would be the interaction of these generators under a system disturbance. The resultant voltage transients are determined through stability analysis of the system.

2.5.1 Transient stability

In any Utility Distribution power system, it is mandatory that system frequency and voltage magnitudes are kept close to the nominal values at all times.

Power system stability problems are typically classified according to three criteria: Firstly, distinguishing between angle and voltage stability. Angle stability is caused by the lack of synchronizing torque between synchronous generators. Voltage stability refers to the ability of a power system to maintain steady voltages at all buses in the system after being subjected to a disturbance from a given initial operating condition [7] [10]. It depends on the ability to maintain/restore equilibrium between load demand and load supply from the power system. Instability that may result occurs in the form of a progressive fall or rise of voltages of some buses. A possible outcome of voltage instability is loss of load in an area, or tripping of transmission lines [3]. Stability problems are divided into short term and long term effects. In non-linear systems, there are generally three different ways, instability can occur viz.: lack of a stable equilibrium, lack of attraction to a stable equilibrium and lack of damping [2].

Significant integration of DG can affect significantly all types of stability, i.e. angle, frequency and voltage stability [16]. When small scale distributed generators are connected in small amounts, the impact of distributed generation on power system transient stability will be negligible. However, if its penetration level becomes higher i.e. a generator affecting a far larger part of a distribution network and possibly the transmission network, distributed generation may start to influence the dynamic behaviour of the power system as a whole [1], [13].As long as the penetration level of distributed generators in the power system is still low and they only cover a minor fraction of the system load, the impact on the dynamic behaviour of the power system is minimal [1]. When the penetration of DG is high, the generated power of DG units not only alters the power flow in the distribution system, but in the transmission system as well.

For the distribution network, the transient stability of the entire system is not as important, since even in the case of the instability of all DG units, they are tripped by the point of utility protection [6] and the system returns to its normal mode of operation. If the external system is represented as a voltage source of infinite power, there will be no problems with the active/reactive power balance both in the static and dynamic sense [3]. This implies that there will be no problems with frequency and voltage stability. For the above mentioned reasons, only the transient stability of the distributed generators is analysed rather than the transient stability of the entire system [3, 10].

In a multi-machine environment as in figure 2-20, the importance of damping of individual machines or groups of machines is related to the inertia of these machines [4]. The smaller the inertia constant of the machine the transient instability of the machine occurs faster and therefore results in a linear relationship [3]. It is the damping of smaller inertia sources that determines the damping of inter-machine oscillations. This is important where distributed generation sources with small inertia characteristics supply partially distributed loads [4].

As mentioned previously, Distribution electrical infrastructure strengthening projects are derived from the Utility’s network development plans (section 2.3.2). These plans may or may not become a dependency to a DG project. If they are, the utility may prior to preliminary design stage alter the engineering solution to accommodate the interconnection of the DG plant. However, if a DG project, due to its viability is constrained to an area in which no utility plans exist or neither are additional plans feasible, i.e. from a cost perspective and electrical interconnectivity sense, then technical limitations constrain the project. In such instances to integrate DG projects to the grid, may present many instability scenarios.

Some of the technical implications shown of system planning are [14]:

a) To determine whether DG can be integrated cost effectively

b) Issue standards and guidelines, and assess the depth of penetration

c) Specify interface systems between DG and the distribution grid with the relevant protecting devices;

2.5.2 Fault conditions

Fault conditions common on distribution lines will also be a factor that leads to such scenarios. Faults types are classified into transient and persistent; and can either be symmetrical or asymmetrical. A transient fault is a temporary short circuit condition until power is disconnected. Many faults that occur in overhead power lines describe transient functions. A permanent fault causes voltage sag to customers on a MV network feeder. Most faults in power systems are unbalanced. Asymmetrical faults do not affect each of the three phases equally. Examples are line to line faults, line to ground faults and two lines to ground faults. In HV grids fault ride through capabilities (sustaining the fault condition without any tripping) are used to maintain stability during such disturbances [12].

With regards to the above fault conditions, problems might appear also due to the fact that short-circuits occurring in distribution networks are cleared in rather long times (in some cases due to the mechanical operation of the relay device). A very common indicator of transient stability of synchronous generators is Critical Clearing Time (CCT) which is defined as the maximum duration of the fault which will not lead to the loss of synchronism of one or more generators [4]. They can therefore cause transient instability of the distributed generation in terms of both the rotor angle and the fast part of the voltage stability phenomena, as mentioned above. Instabilities may result in the outage of a large amount of generators in the neighbourhood of the disturbance and consequently to cascading events. [2]. For the type of network and generator considered in study case 2, the CCT was found, depending on the location of the generator within the network, to vary between 0.1 and 0.5 sec [3]. The CCT time chosen in this dissertation is 100ms.

2.5.3 Rate of change of frequency

Rate of change of frequency relays (ROCOF) are typically used in the protection at the point of DG connection and are used to detect islanding conditions, i.e. the loss of upstream network [6]. As mentioned in 2.5.1 above, where the stability of the entire system need not be analysed on the advent of a disturbance [3], but where the DG plant inertia is low and the tripping time of the protection is long, it may not be possible to ensure stability for all faults on the distribution network. With a large system disturbance, such as *the loss of a large system generator*, the ROCOF relays may mal-operate and trip large amounts of DG. Synchronous generators will pole-slip during transient stability and induction generators will draw large reactive power leading to voltage instability [16]. The analysis of voltage stability discussed further in the thesis will therefore use the scenario of losing large amounts of generation in a stable grid and monitoring the voltage at relevant station busbars.

Although ROCOF relays detect islanding conditions, their use is somewhat restricted to the type of voltage to which they operate. For networks with voltages less than and equal to 33kV, ROCOF relays work well but industry projects using this protection for voltages greater than 33kV have not functioned correctly and have resulted in huge losses in damage to generator plant equipment. To mitigate this problem, an alternate direct-trip scheme such as using fibre optic or radio communications can be employed to trip upstream breakers thus avoiding the generator plant feeding into a common coupling point of network.

2.5.4 Voltage rise on medium voltage networks

When generated power exceeds the load of a MV distribution feed, voltage rise will occur. This voltage rise caused by the reversed power flow is a function of the power generated by the DG and the short-circuit power of the grid at the point of interconnection.

An operational approach can be to restrict the operation of the DG unit during off peak load times and so expensive grid strengthening can be prevented. This can be an attractive alternative when the DG unit is dispatched. DG units including synchronous machines can absorb some reactive power and in this way can help reduce voltage rise but in controlling the voltage level by controlling the reactive power flow, only works for distribution feeders with adequate X/R ratio. The voltage rise is a steady effect and strongly depends on the X/R ratio, feeder load and DG injected power. A rapid load current variation of a DG unit causes a sudden increase or decrease of the feeder current and hence an effect on the feeder voltage (transient effect).

In [13] three worst case scenarios were defined as:

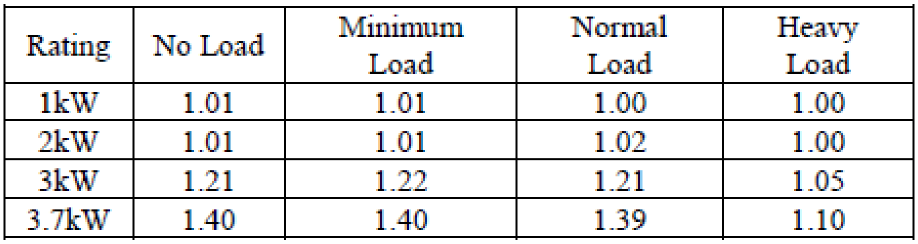
- minimum load maximum generation
- maximum load minimum generation
- maximum load maximum generation

It has being shown in [13], for a large system that ***"****the voltage variation in a distribution network with distributed generation, is directly proportional to the amount the active power supplied by the distributed generators****".***

$$\Delta Vworstji \propto PGjmax \tag{2-3}$$

For urban and rural MV networks, peak voltages with individual increasing switching operations were investigated [17].

Table 2-2. Peak voltage magnitudes at consumer bus under different load combinations and increased sources [17]



Rating	No Load	Minimum Load	Normal Load	Heavy Load
1kW	1.01	1.01	1.00	1.00
2kW	1.01	1.01	1.02	1.00
3kW	1.21	1.22	1.21	1.05
3.7kW	1.40	1.40	1.39	1.10

The results in table 2-2 above clearly show that when the generator outputs are high and exceed the connected load, appreciable over-voltages would occur. This shows that on weak MV networks during light load conditions, the load is insufficient to absorb the injected generation and such appreciable over-voltages would occur. The solution to mitigate this is can be quite costly and cannot be easily implemented. For urban and rural networks, the voltage peak increases with feeder load and coincident switching operations as shown graphically in figure 2-25 below [17]. In addition, from the results it was concluded that rural networks are far more susceptible to switching over-voltages where multiple sources are involved and a linear relationship between the number of generators and peak voltages is established. No significant over-voltages in either scenario analysis on generator disconnections.

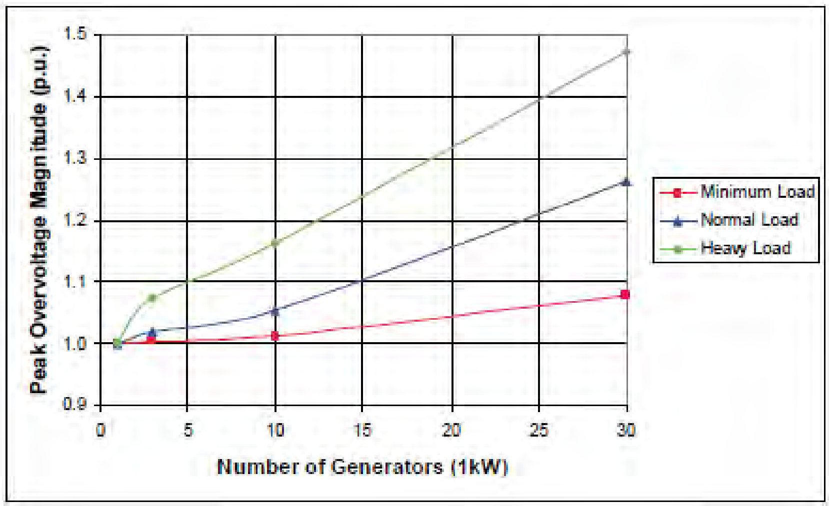


Figure 2-25. Variation of peak over-voltages in an urban network with number of generators and local instantaneous load (switching in) [17]

2.5.5 Wind and Solar PV stability

Most wind turbine generators are often isolated from the network grid by means of electronic converters, so their initial response to the overall power system is almost negligible [27]. Solar PV plants have no contribution to the inertia of the grid system. This implies that an increase in the penetration of wind turbines and solar PV plants may result in large changes to the dynamic performance and operational characteristics of the power system in which synchronous machines previously dominated [27] and it is for this reason that voltage stability is investigated in the sections that follow.

A high penetration of wind farms could reduce the effective inertia of the entire power system. As the inertia reduces, the power system becomes more sensitive to generation-load balances especially during off-peak times. However, wind plants can actually help in stabilizing the power system by providing low voltage ride through capability and dynamic VAR support to reduce voltage excursions and dampen swings [27]. Large solar farms can change output by +/- 70% in a time frame of two to ten minutes, many times per day.

A PV (Power-Voltage) stability study is the analysis of the transmitting of power from one region to another and monitoring the effects of system voltages.

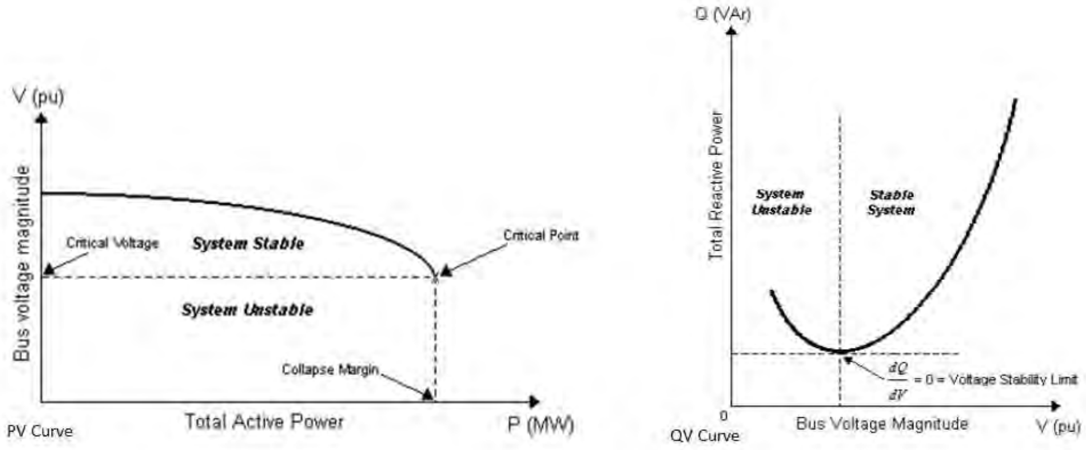


Figure 2-26. Typical PV and QV curves [64]

At the critical point of the PV curve in figure 2-26, as the load demand increases, the voltage drops off rapidly and the system is deemed unstable beyond this point. A typical Q-V curve as in figure 2-26 above is plotted such that an increase in Q (reactive power) will result in an increase in voltage during normal operating conditions. The P-V curve is plotted for constant power factor and the Q-V is plotted for constant power.

In [65] a stability analysis of the electrical power system of Puerto Rico is conducted by observing the impact of the proposed increase in wind power generation. PV curves were used to study the voltage stability of bus 15 of the electrical system. Three areas of wind generation were modelled. It was shown that increasing wind power generation on the northern wind farms from 50% to 100% increases the critical voltage on bus 15 and while lower wind levels of 25% decreases the critical voltage [65]. This case study demonstrates the use of PV curves to estimate the penetration levels of wind generation.

A method was located in [18] in finding the steady-state voltage stability region for each bus of a distribution power system considering the presence of wind power generation. In addition the maximum permissible load that can be connected to each bus with this generation is also discussed. It is concluded that P-Q curves are best suited in choosing an operating point for the wind farm.

2.5.6 Concluding research

Many studies have been undertaken investigating the effects of wind integration to the grid as mentioned previously and methods in locating stability regions have been investigated. [18].From the assessments of technical plans that are derived by many international directives, focus to achieve National targets for greener energy, comprises majority of renewable resources that utilize synchronous machine technology [55] [56]. The problem of having close proximity plants sharing common infrastructure is quite probable and mechanisms to assess these connections are required to be established. Three sets of study cases are identified which focuses in finding methods in assessing synchronous machine technology. The first is required to assess the system under steady state conditions, the second voltage stability conditions and the third a mechanism to physically integrate the distributed generator and grid together.

2.6 General methodology used in the analysis

2.6.1 General method of conducting the research work

The method chosen to establish the design criteria of the simulations in chapter 3 is to minimise the exploration of too generic models and to use typical design components of models that are currently employed in the industry. This type of research is far more practical and realistic. Software modelling on existing network systems was chosen as these simulations apply to real-life case studies which are intended to narrow the gap of the level of accuracy in the concluded results. The required information for the studies was accessible through various interactions of sources in the utility and electrical industry.

2.6.2 Data collection and analysis

The high voltage power system in Eskom distribution is modelled in DIgSILENT Powerfactory [30]. DIgSILENT Powerfactory is a power systems tool used for the analysis and design of electrical networks. DIgSILENT has the functionality that components and functions in the analysis tool can be controlled by scripts that are written in the DIgSILENT Programming Language (DPL) [30]. This language therefore provides an interface to the user for the automation of tasks in Powerfactory. Using this defined programming language; one can define automatic commands in scripts, to perform iterative or repetitive calculations on specific networks. In order to perform the tasks to meet the objectives of this thesis, a learning curve of DPL was required. The initial help on DPL (V14) was quite limited compared to the latest version 15 that is now active.

The analysis of all the relevant studies had a similar approach. Powerfactory models were firstly built and DPL was then used to control the various elements making up the model. The data that was collected was analysed in Microsoft Excel using Visual Basic programming language to sort thousands of iteration values for various power system parameters. In addition, all GIS work was analysed using ARCGIS software [57]. To meet the objectives of the research, the following four tasks were defined for each objective:

2.6.3 Objective 1 met by Design 1: Penetration Paths

The DPL script designed to identify the single critical path of components to which combined generation control, makes use of the summation of the fault current value at a specific point. All electrical equipment has a fault current rating that determines the equipment strength during a short circuit condition. A model that represented a subset of an electrical grid was chosen as an entire electrical grid model would increase the risk of error that could be time-consuming and defeat the purpose of the study (figure 3-4). This model was built in DIgSILENT Powerfactory to utilize the DPL scripting function as explained above. Thus the magnitude of generation and the number of electrical components could be easily controlled. This was important in the testing of the solution script, firstly to reduce error, and secondly to have noticeable changes in the connected system with changes to specific component parameters.

2.6.4 Objective 2 met by Design 2: Grid Voltage Stability

For this study, a more generic model was built in DIgSILENT (figure 4-5). This study made use of two common electrical network topologies, viz. radial and loop-in-loop-out configuration. A radial feed implies that a single source supplies the load and in the loop-in-loop-out configuration, two or more meshed sources maintain supply to the same load. DIgSILENT Programming language (DPL) scripting was once again used to control the iterations in the analysis. The simulation study was much more complicated as the stability functions in DIgSILENT Powerfactory were used and controlled via DPL. The resultant data was analysed using Visual Basic programming language and statistical methods.

The designed model made use of “external grids” to control the network strength. These grids in the simulation are sources that have maximum and minimum short circuit values that provide a stable voltage bus. These short circuit values can be changed to execute the effects of strong or weak sources. Furthermore, line distances were fixed and machine increments were applied to all connected synchronous machines with changing values of the external grid sources. Changing network strengths from various network points implies change in the upstream network impedance, hence fixing the line impedance. It is assumed that the line inductance does not significantly affect the results as the intention is to model proximity large generators for reasons explained in section 2.5.1. Also, upstream impedance change, typically a reduction, practically implies network strengthening, new transmission injections or different network operating conditions.

2.6.5 Objective 3 met by Design 3: Network connecting models

These models were derived from existing utility line and substation design models to which the selected components meet the relevant design specifications [45, 46]. These models utilise various design type element data to derive results of knowing which connecting type model to use. Costing is calculated from the various utility design costing tools.

2.6.6 Case Study: PV mapping and connection assessment for KZN

This study used solar irradiance mapping to provide a MW output for a particular geographic area which was quantified for a particular region in South Africa. The relevant mapping was sourced from ESRI GIS [50] and SOLAR GIS [51] companies. No design cost to the mapping was incurred due to the data been freeware. This data was then analysed using ARCGIS software [57] and the results modelled in DIgSILENT Powerfactory. DPL was again used in the analysis.

The designs of all simulations are presented in the next chapter. Each objective above is met by the relevant design.

3 Case Studies - Design and Simulations

This chapter presents the case study designs and simulations that were used to derive the technical planning criteria for the integration of the two renewable resources discussed in chapter 2.

The first design establishes a mechanism of analysing the effects of distributed generating units (synchronous machines) sharing high voltage networks on any part of the utility electrical grid by finding a set of affected network components. The second design creates a generic grid of two connecting network topologies (radial and loop-in-loop-out) and replicates any part of the utility electrical grid. This design is controlled by two sources that change the network strength i.e. the system fault level at those points. The changing source inputs are to analyse the network voltage stability at the high voltage busbars during the loss of varying bulk generation during peak load. The third design adds to existing industry substation configurations, providing a guideline to DG integration with a planning cost estimate. Flowcharts' explaining the compilation of the DPL code used in designs one and two are presented as well as the flowchart showing the process of design three.

3.1 Design 1: To establish a mechanism of locating a critical path of planning components

As mentioned in previous chapters, it is imperative to identify electrical network infrastructure that requires upgrading or re-configuring to maintain network integrity and quality of supply. A distributed generator may be connected to any part of a network and this network may exist in various states i.e. be expanding rapidly or in future plans may be radial in nature or have varying power carrying capability based on operational procedures. It is therefore essential that the model created in this design must account for any of the above scenarios. This design provides a mechanism for finding a list of components, in the path of distribution network affected by a generator. In establishing these components, the utility can better plan projects to cater for potential generation thus improving the accuracy of development plans.

A generic electrical grid was simulated in DIgSILENT Powerfactory [30]. The grid was designed to consist of synchronous machines connected to any busbar on the secondary side of high voltage transformers. Typical element type data for line types and transformer types, as available in DIgSILENT library were used. The algorithm that was compiled using DPL scripting language is not dependent on specific element type data.

The DPL script developed uses two methods to interrogate the grid. In the first method, the algorithm locates the generators under scrutiny and then finds the cumulative effect of injected fault currents of all generators, at each relevant busbar. The second method starts from a user defined list of generators for the analysis. The first generator is selected and the script works through the network until the script input parameter is satisfied. This parameter defined as the *variance parameter* is explained further in section B. The two methods are explained below.

A. General selection (brute force technique):

This algorithm selects all synchronous machines irrespective of whether the generator exists, is new or connected to another part of the grid where there is little impact. This algorithm selection applies to many distributed generators in close proximity and is a quick solution to smaller electrical grids. If other interconnecting grids contain generators that provide inputs to, for example, transmission stations then this method will *not* work as these stations will be appended to the new generators for analysis resulting in, incorrect results.

B. Iterative approach using the Viterbi decoding algorithm.

This approach also applies to multiple generators in close proximity or distances apart but more importantly, distributed in large electrical networks where not all connected synchronous machines are required to be analyzed. In addition, simulation iterations are reduced due to the dissipating generator effect (fault level increments) through the grid.The Viterbi algorithm is commonly used in digital decoding of data but has been partially adapted here in the structuring of the code sequence used to successfully compile the DPL program [28]. The Viterbi algorithm can be described using a trellis. In this trellis, each node corresponds to a distinct state at a given time, and each arrow represents a transition to another newer state [52]. For every possible state sequence, there is a unique path through the trellis [52].

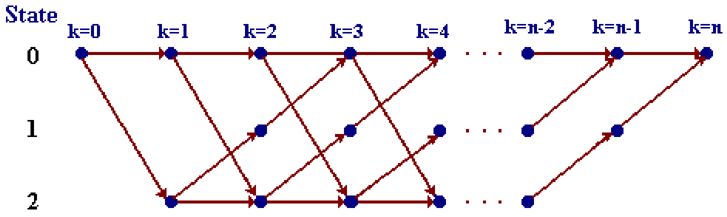


Figure 3-1. Viterbi algorithm [52]

The adjusted algorithm is explained as follows:

- Start at the point of generator connection; expand at the connected node and then at each set of connected elements.
- The point of expansion is defined by a set of calculations that define the generator injection at that point. If the fault current injection of the distributed generator contributes to that point, then expand that point of connected elements further until the contribution equates to zero or to a pre-set value, to which the author defines as the *variance* of the DPL program [29].
- The common elements in the path of calculation (continuously stored in a set) are then defined to be the critical path of components that the generator affects. However, the algorithm as shown in figure 3-2 has been adjusted such that it can take into account the fact that in larger grids, more than one critical path may exist. This implies that several nodes may be expanded in a set. It is in this set that the Viterbi algorithm differentiates the number of elements defined as 2^n, where '2' represents '0' or '1' in digital decoding and 'n' represents the number of states.

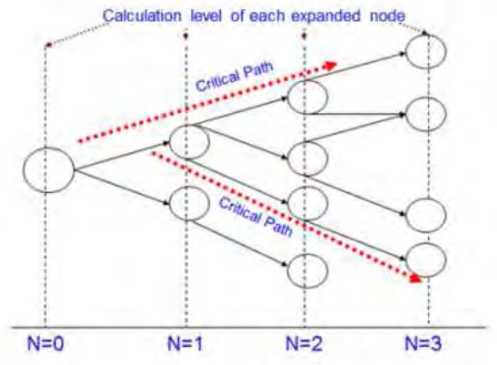


Figure 3-2. Reconfigured algorithm

In figure 3-2, *N* represents a network layer. The total number of elements (S_n) is therefore defined as *critical path of components* and can be simply expressed as:

$$S_n = N_0 + N_1 + N_2 \ldots . N_x \tag{3.1}$$

Where x = that layer in which the variance parameter, VP = 0.

$$S_n = \sum_0^{VP} \mathrm{Nx} \tag{3.2}$$

The following symbols used in figure 3-3 can be defined as follows:

C(0) = Brute force option

C(1) = Iterative option

S_M = set of all machines (M)

n = n^{th} element (busbar)

m = m^{th} machine

$N_{1..x}$ = all elements of expanded node

{N} = set of all affected elements

US_m = user selection of machines

The flowchart that follows describes the sequence of events that run through the DPL script.

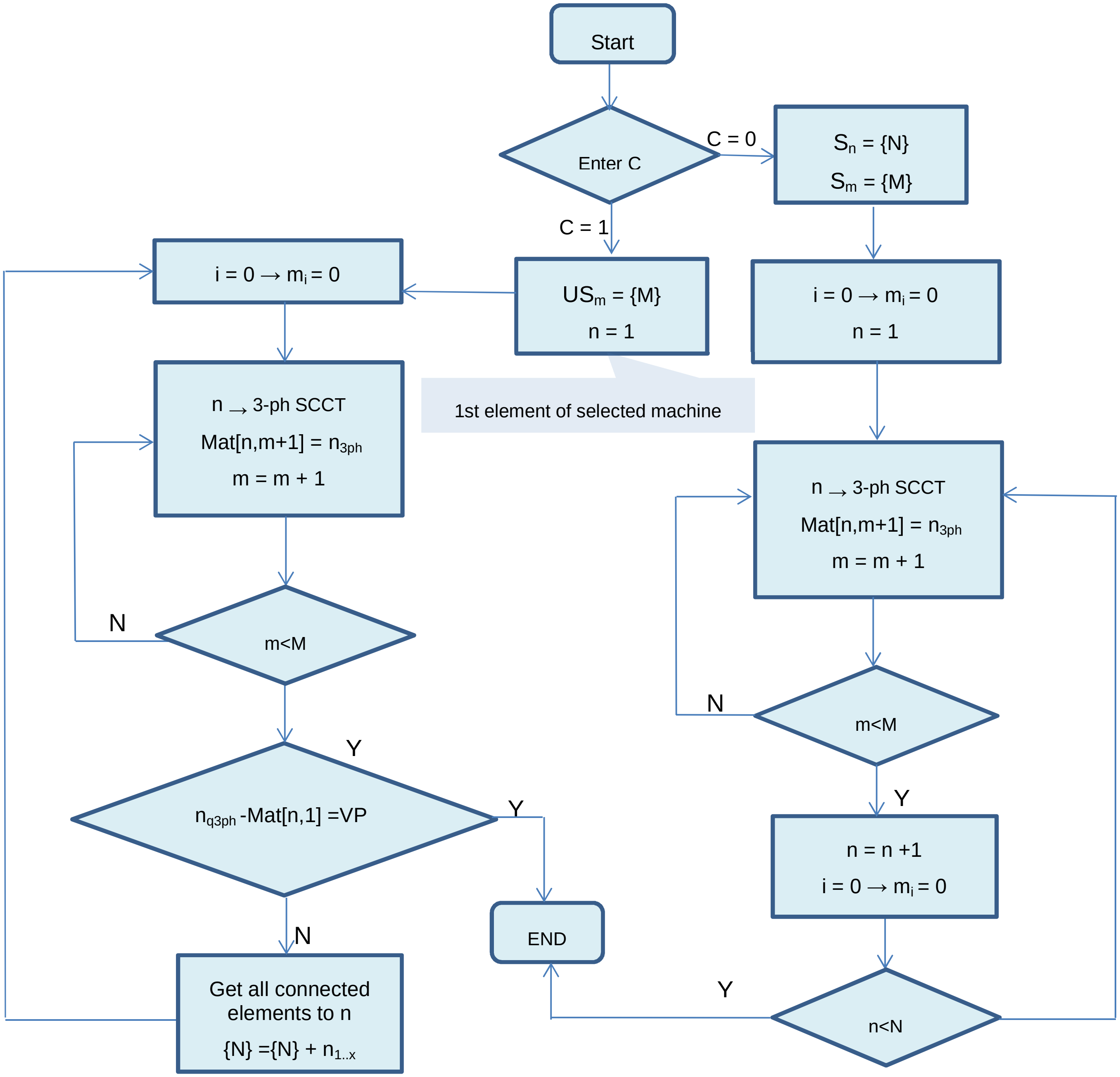


Figure 3-3. Critical path flowchart

The flowchart in figure 3-3 is explained below. The script when executed requires the user to input *0* for the brute force option and *1* for the iterative option (“Enter C”).

A. Brute force execution

In choosing the brute force option, two sets of elements are collected. The first is a set of all the connected synchronous machines and the second the set of all terminals *(Sn,Sm).* Terminals are defined as a set of relevant busbars and connecting points of line and cables. A terminal element is chosen from the set and with the initial base case of having all the machines out of service ($m_i = 0$), a short circuit three phase calculation is executed on that element (n_{3ph}). Once calculated, the result is stored into a matrix *(Mat).* When this is completed, every machine in the grid is then switched on and a short circuit three phase calculation is then performed on the same element and the calculated short circuit current value is again stored in the matrix. With the base case values, the number of columns in the matrix is determined by the number of machines and the number of rows is determined by the number of collected elements (*Mat[n,m+1])*.

B. Iterative execution

This option starts by requiring the user to select certain machines that are required to be analysed in the grid. These machines are stored into an array (US_m). The script starts at machine one, calculates the base case fault level and stores this value into the matrix. Thereafter each machine in the array is turned on and the resultant effects of the machines on the connected element of machine one is again tabulated into the matrix by completing a short circuit analysis (*Mat[n,m+1])*. A new array *({N})* then stores all elements connected to the element of the machine. The short circuit analysis is then computed at each connected element in the new array and the resultant effects of each machine turning on are again recorded. When the computation of the short circuit analysis is performed on the element and the difference in base case value and the value of all machines combined equals the defined variance parameter *(VP),* then the script then checks if all paths are covered in the same manner and hence a new set of elements identifies the critical path or that part of network that is affected by the combined generation ($\{N\} = \{N\} + n_{1..x}$).

The grid in figure 3-4 below was used to test the DPL script. The grid has four connected synchronous machines connected to the secondary side of a 132/11kV transformer, which is a typical high voltage distribution transformer type used in the utility. This grid configuration is chosen such that an adequate number of elements can be analysed. For this analysis, the magnitude of power is not relevant as the varying fault current contribution is the measurement that is required. DIgSILENT Powerfactory regards connecting busbars as terminals and it is at these check points to which single-phase short circuit and three-phase short circuit calculations are performed for different on/off generator combinations. If a particular component had a change in the fault level value for either condition, then this component is moved into a set, and once all possible iterations are executed, the set would reveal all components that make up a path in the grid defined as the “critical path” as mentioned and explained above. The magnitude of fault level variance, also defined above as the *variance parameter* determines the contents of the set and ultimately the ‘length’ of the critical path. The larger the parameter the shorter the path i.e. fewer components are obtained in the set. The element data used is shown in table 3-1.

Table 3-1. Element data used in the model [45]

Data type	Type specific
Line	132kV Kingbird and Wolf conductor – Single circuit
Transformer	132/11kV 20MVA, Z = 7%
Sync machine	Xd” = 0.2, 4.5MVA at 11kV, p.f = 1

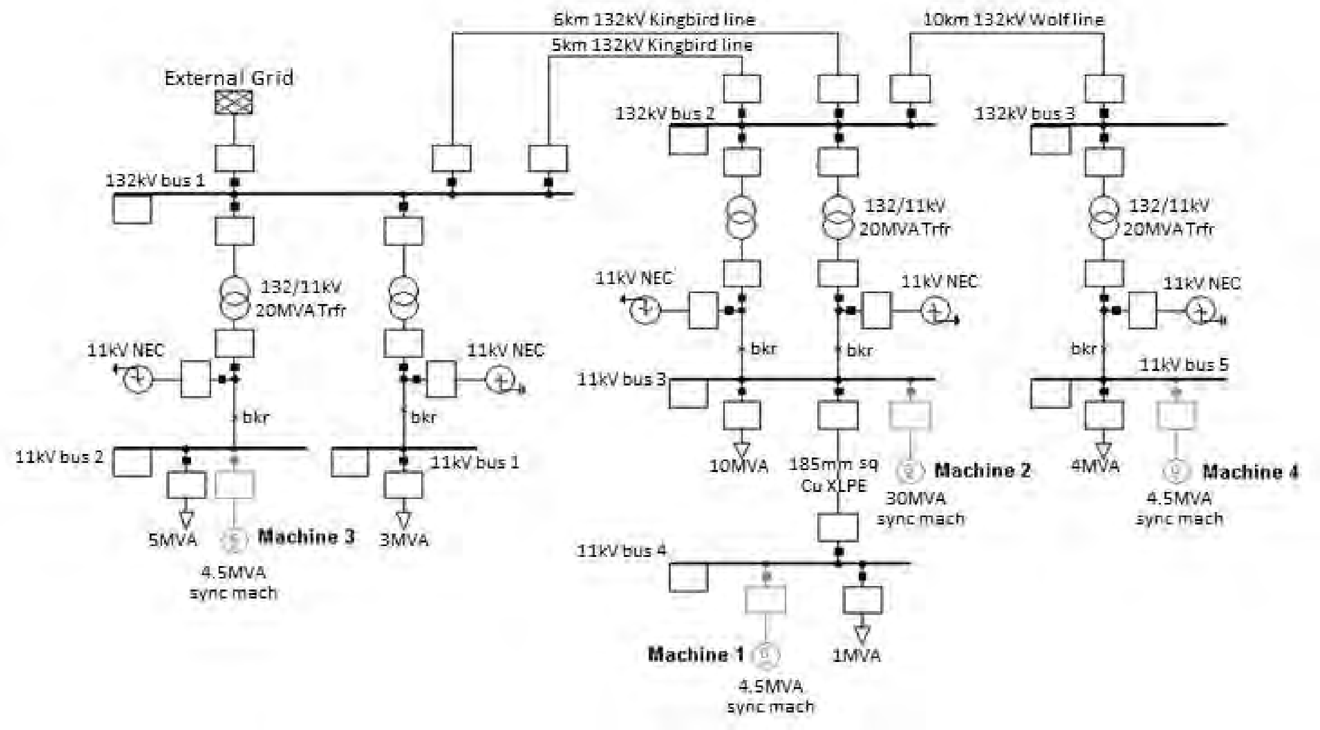


Figure 3-4. Test grid used to develop the DPL script

3.2 Design 2: Generic grid design for voltage instability studies

In design two, a method of planning infrastructure in a grid that has a potential of many distributed generators connecting to the same infrastructure is developed. This addresses interconnectivity requirements. This method should be used as a rule of thumb to a planning engineer. By knowing the existing network strength and the amount of bulk generation that can be lost during peak load, the engineer should be able to determine how much distributed generation can be connected in that network without any voltage instability issues.

An electrical network of a typical high voltage case study is modelled in DIgSILENT Powerfactory. Synchronous machines are connected to distribution high voltage 132kV busbars. In order to make the approach more generic, two common electrical network topologies are analysed, a loop-in-loop-out (alternate/redundant supply point) and radial (single supply point) network configuration [8]. The operating model is controlled by two external grids that control the network strength under certain defined conditions. These grids allow the network impedance to be based on the short circuit power and impedance angle [30]. The time of operation and generator size is varied to provide as much data as possible such that accurate conclusions may be derived. The algorithm, detailed to a certain extent in the flowchart in figure 3-8, changes the values of both grids and the number of machines. By doing this one can determine from the results what machine sizes affect the voltage stability at the relevant busbar. Each time a value is changed a stability analysis study is executed and the values that describe the response curve function are stored.

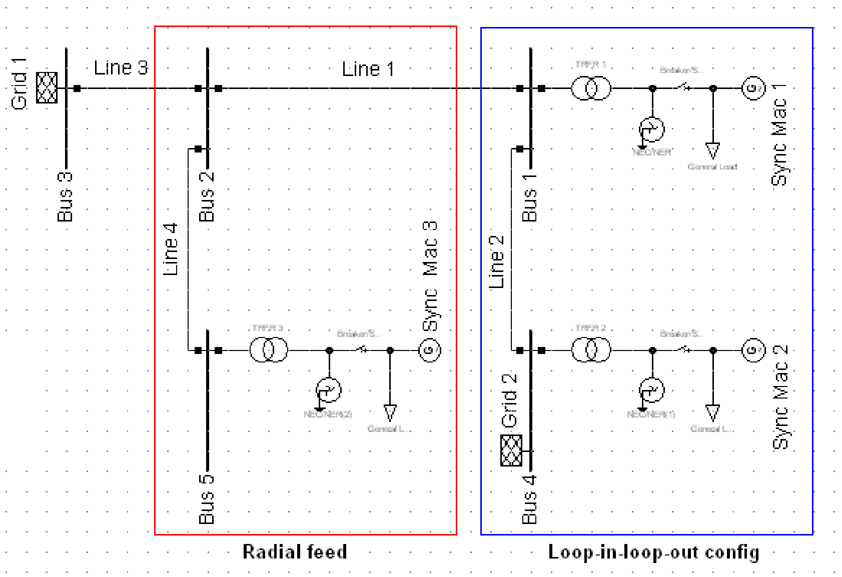


Figure 3-5. Test grid model used in the analysis of design 2

Two scenarios have being considered to provide the simulated data. The first is the system supplying peak load and the sudden disconnection of one of the three generators which is (shown in figure 3-5) which leads to voltage instability and the second being three phase fault conditions also during peak loads, occurring at the generator connected busbar and upstream in the network.

In the test grid of [15], the location and the size of the generator are modified in repetitive calculations. The setup *("Fig.15.Overview of the simulated distribution grid.")* shown in [15] has being adapted to the test grid used in this thesis and multiple loops provides many different scenarios used in the study.

A. Network Model control conditions

With reference to figure 3-5, the following control conditions bound the simulations that follow:

1. The renewable resources under scrutiny are synchronous machines which represent hydro schemes and biomass facilities. Many research papers have focused on wind generation facilities and this technology as well as solar technology is therefore excluded from this study. Solar PV analysis is investigated in the case study in chapter 5.
2. The structure of the network has a radial feed connecting synchronous machine 3.
3. The structure of the network has an adjoining loop-in-loop-out configuration connecting two synchronous machines. The loop-in-loop-out configuration implies reliability of the network [8].
4. Two external grids are connected. Grid 1 ($n_{g1} = Mat[i,1]$) acts to provide the main infeed into the system and varies its network strength thus simulating a network expansion up to a certain fault level. Grid 2 ($n_{g2} = Mat[i,2]$) provides similar functionality as the redundancy source feed.
5. Line lengths and impedances per unit of line length are kept constant as the impedance is controlled by the external grids [30].
6. Multiple iterations of different scenarios change the connecting loads, machine electrical power output, external grid input levels and fault current injection (m_i) by keeping the sub-transient reactance *Xd"* constant and at an typical level of 0.2.
7. The limitations that bound models of previous research papers were electrical grid interconnectivity that formed a fraction of a utility network, large computation time and many scenarios [1]. By using DIgSILENT Scripting language (DPL), the elements in the model are controlled considerably to provide a more generic

approach to the conclusions of the study. Also, because of the amount of data derived from each simulation, Visual Basic excel code was used for data manipulation.

The flowchart below describes the sequence of events and coding of the above study. This is the first step in DG analyses and involves calculating the fault level at each connecting busbar and terminal connection point, due to the fault current injection of the connecting generator. It has been shown that [2], all generators connecting to the same High voltage infrastructure contribute fault current to any point within that system, and that a critical path exists to which all the electrical elements all affected. This implies that connecting equipment may or may not be suitably rated to withstand the generator under any fault condition. To provide a varying system of inputs of network strength, three phase and single phase fault levels of the Eskom KZN Distribution High Voltage system are used [47].

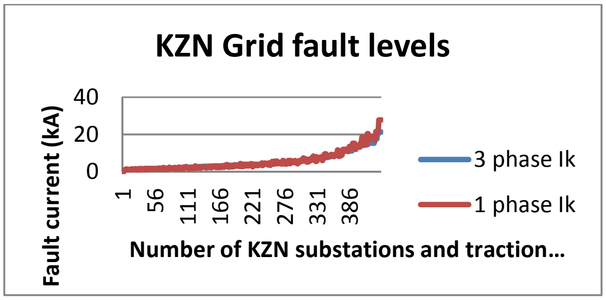


Figure 3-6. Eskom distribution grid fault levels in KZN [47]

From figure 3-6, it can be seen that the deviation of the three phase fault level from the corresponding single phase fault level is minimal and simplifies the grid inputs thus reducing the establishment of the relationship ratio between the two levels. For the ease and reduction in error analysis, the study is divided into three stages. Each stage is characterised by a fault level range. The first stage is limited by a 5kA network strength, the second from 5kA to 10kA and the third from 10kA to 15kA.

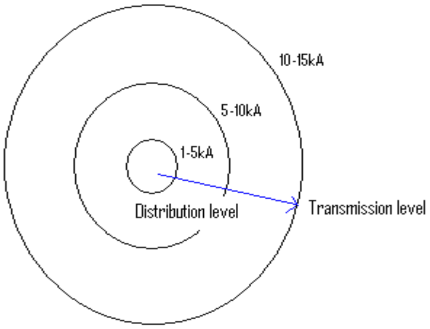


Figure 3-7. Distribution network divided into stages

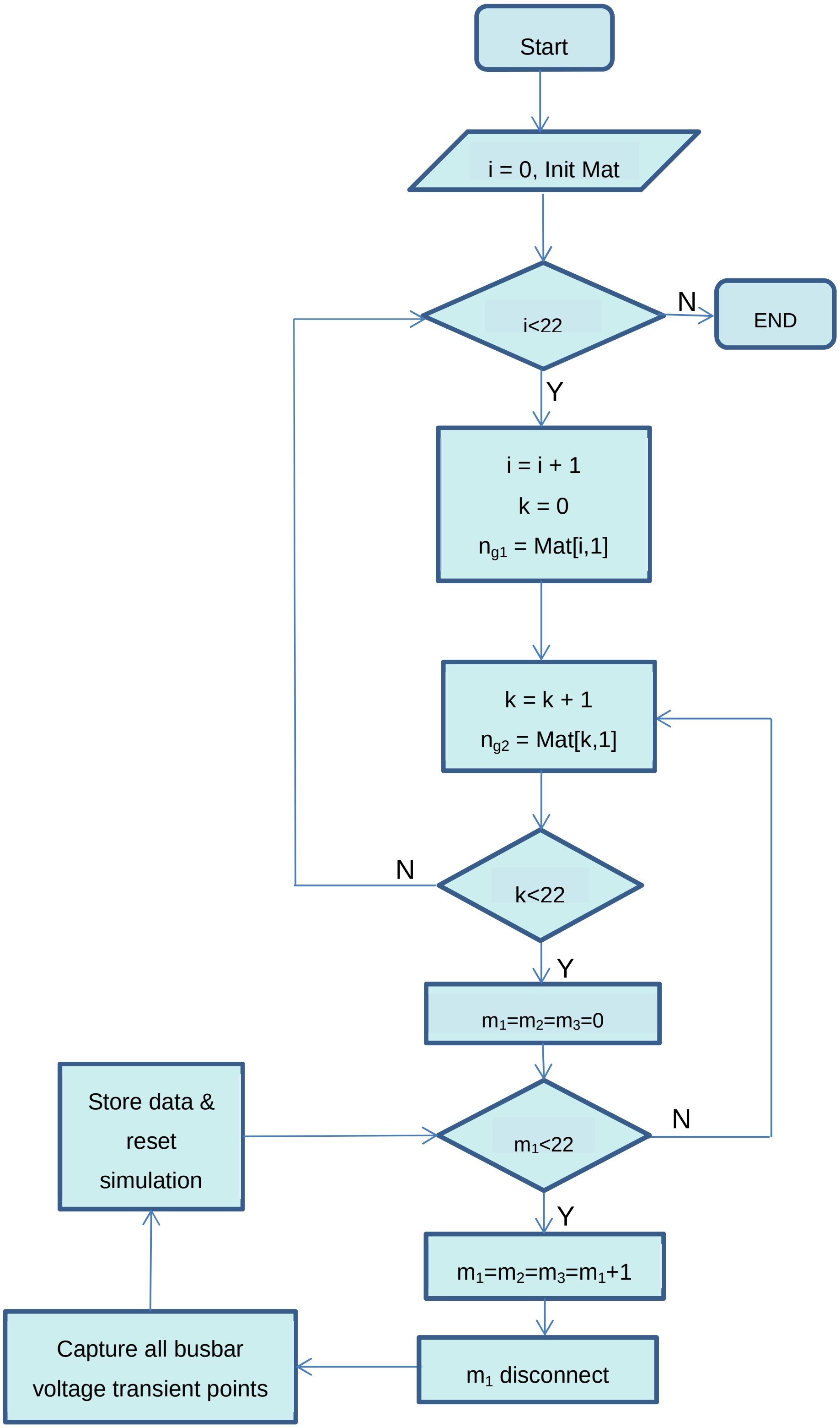


Figure 3-8. Stability analysis flowchart for design 2

The flowchart in figure 3-8 is explained as follows. The matrix values $n_{g1 \text{ and }} n_{g2}$ are the grid values of matrix *Mat* in table 3-2. These values are the input values to the external grids in the model. The script starts by holding the value n_{g1} constant using the iterative index *i*, holding the value n_{g2} constant using the iterative index *k* and then moving through the number of machines (total = 22). For each condition, machine m_1 is disconnected at full load. The result of each busbar is the voltage transient that occurs at the disconnect. Each point that describes the voltage stability curve is then stored and m_1 re-connected. The next combination of inputs are controlled by the above 3 indices and the output data is then saved per the three stages shown in figure 3-7.

Figure 3-7 shows diagrammatically the manner in which networks are built and radiate outwards towards distributed load. The characteristics of the figure shows a decline in fault level, due to summation of network (line) impedances from the Transmission network to the Distribution network. Two scenarios are considered. The first being the sudden disconnection and reconnection of generator 1 within the CCT (150ms) and the sudden complete disconnection of generator 1, both during peak load. With the two network strengths controlling the model, one is able to clearly define values to which different network strengths interact with different generator sizes and make an adequate descision descrbing the network stability. The analysis that is required here is the voltage curve data that results in the change of power activity at each of the corresponding voltage busbars in the generic model.

By using the formula in (3.3) below, the standard deviation (σ) of the data points that trace the voltage stability simulation curve are found:

$$\sigma = \sqrt{\tfrac{1}{n}\left(\sum_{n=1}^{n}(Vd - Vd')^2\right)} \tag{3.3}$$

Where n = number of data points

Vd = data point value in p.u

Vd' = mean of all data points

The data is analysed by finding the ratio of network strength, i.e. with base case fault level and connected generator to grid fault level, to generator short circuit current. Two decision makers filter the results that are required. The first been, the standard deviation rendering the voltage of the relevant busbars unstable and second the voltage regulation that is allowable on a high voltage network as per National voltage regulation standards [5]. Simulation scenarios use the values in table 3-2 to obtain the required results.

A machine value size of 5MVA at 11kV (*Xd" = 0.1499*) is used, as the calculations are simplified. The number of machines is determined by the resultant kA value of 38kA which is 95% close to the maximum fault current ratings of distribution high voltage equipment [48]. All grid inputs as explained previously are determined from the range of values of the KZN distribution infrastructure. It is also assumed that there is sufficient transformation to cater for the power flow and that the transformer impedance is a constant that can be offset from the results.

Table 3-2. Input values to the generic model

Grid 1 and Grid 2				
3 Phase (IkA)	**1 Phase (IkA)**	**No. of machines**	**Fault current (IkA)**	**Gen size (MVA)**
1	1	1	1.750	5
2	1.5	2	3.499	10
3	2	3	5.249	15
4	2.5	4	6.998	20
5	3	5	8.748	25
6	3.5	6	10.498	30
7	4	7	12.247	35
8	4.5	8	13.997	40
9	5	9	15.746	45
10	5.5	10	17.496	50
11	6	11	19.246	55
12	6.5	12	20.995	60
13	7	13	22.745	65
14	15	14	24.494	70
15	17	15	26.244	75
16	18	16	27.994	80
17	19	17	29.743	85
18	20	18	31.493	90
19	22	19	33.242	95
20	24	20	34.992	100
21	26	21	36.742	105
22	28	22	38.491	110

3.3 Design 3: Generic design of connection types

In this design, focus is attributed to the different network voltage types that exist. The two categories that are discussed here are the medium voltage types and the high voltage types. In a distribution system with potential DG, one has either of the above voltage types to connect to and it is thus important to understand the physical nature of such networks. The physical nature explained in the sub-sections that follow describe how these networks are operated, how the components are used to formulate the configuration types and how costs for these configurations can be quantified. This design will then lead to the guideline that one can use from a high level planning phase as a first pass measure on the financials of the project.

3.3.1 Medium voltage (MV) networks (< 33kV)

Distribution medium voltage lines consist of overhead conductor and/or cable [45]. Overhead conductor lines are generally radial in nature with normally open redundant points to other networks. These networks typically feed rural loads including commercial, residential and smaller type industries. Cable networks are generally used in urban areas and typically form a ring network with other cable networks. These lines operate at a distribution voltage of 11kV and 22kV which are generally stepped down to low voltage (<415V 3 phase) at the customers point of supply. MV networks have many tee-offs as shown in figure 3-9 and majority of the time not constructed to cater for any sort of sizable distributed generation. Certain upgrades are therefore required and a demarcation point is also required to be determined as the disconnection point of DG into the MV network. The penetration to such networks was covered in the literature review of chapter 2.

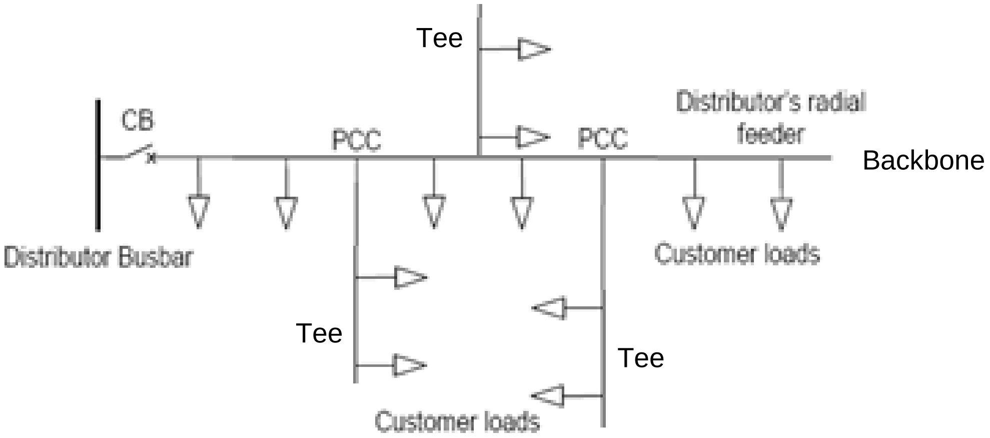


Figure 3-9. Typical MV feeder

3.3.2 High voltage networks (>= 33kV)

The proposed interconnecting configurations were derived from utility based substation and high/medium voltage line design standards [46]. These standards specify equipment types and substation and line design configurations to be used in the construction of the specific assets. Typical line types and their current carry capacities commonly used in South African distribution networks were shown in figure 2-24 (line type specifications). HV lines are typically strung on steel lattice towers which are far more expensive than wooden pole structures used for MV lines above. Structurally they are stronger and larger and require sizable foundations to establish each tower. More and different circuit configurations are available relative to medium voltage

Figure 3-10 shows the typical layout of an outdoor high voltage substation and figure 3-11 shows the typical layout of an indoor high voltage substation. Both types differ as per the medium voltage delivery points. The utility uses these standards as a basis for all substation projects. These designs can be broken into different components. The basic components are demarcated in both figures.

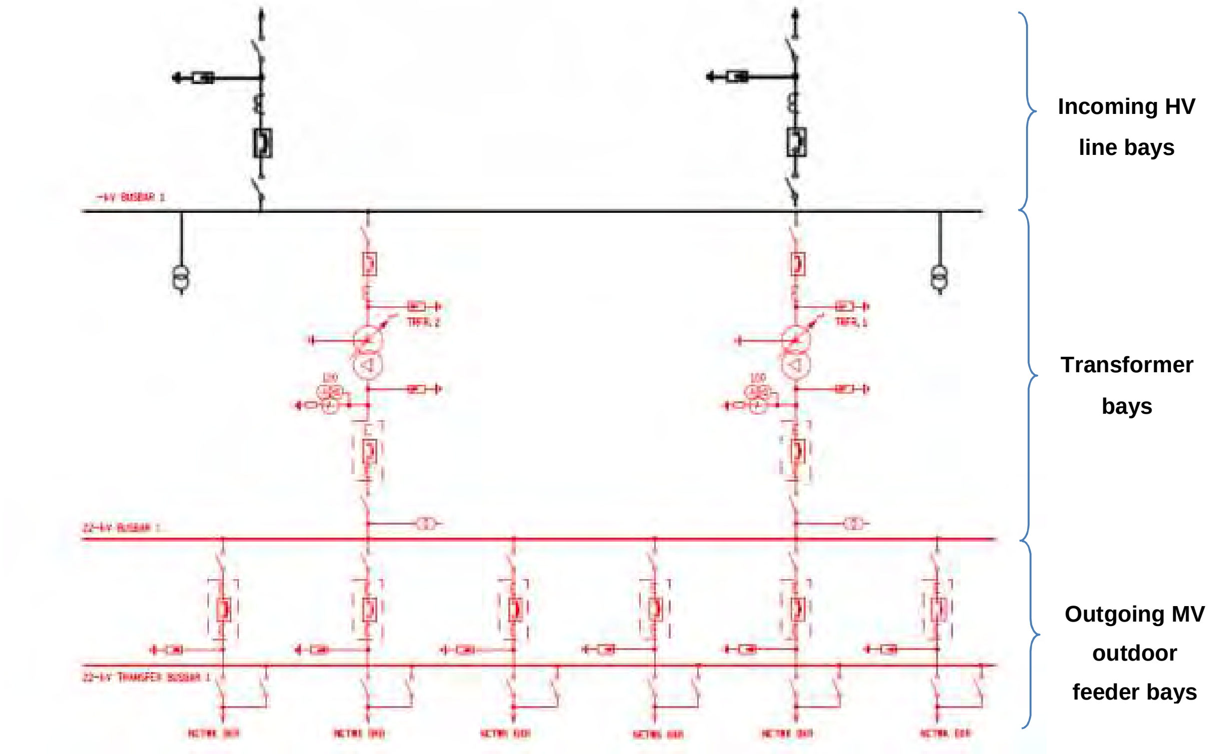


Figure 3-10. Outdoor substation [46]

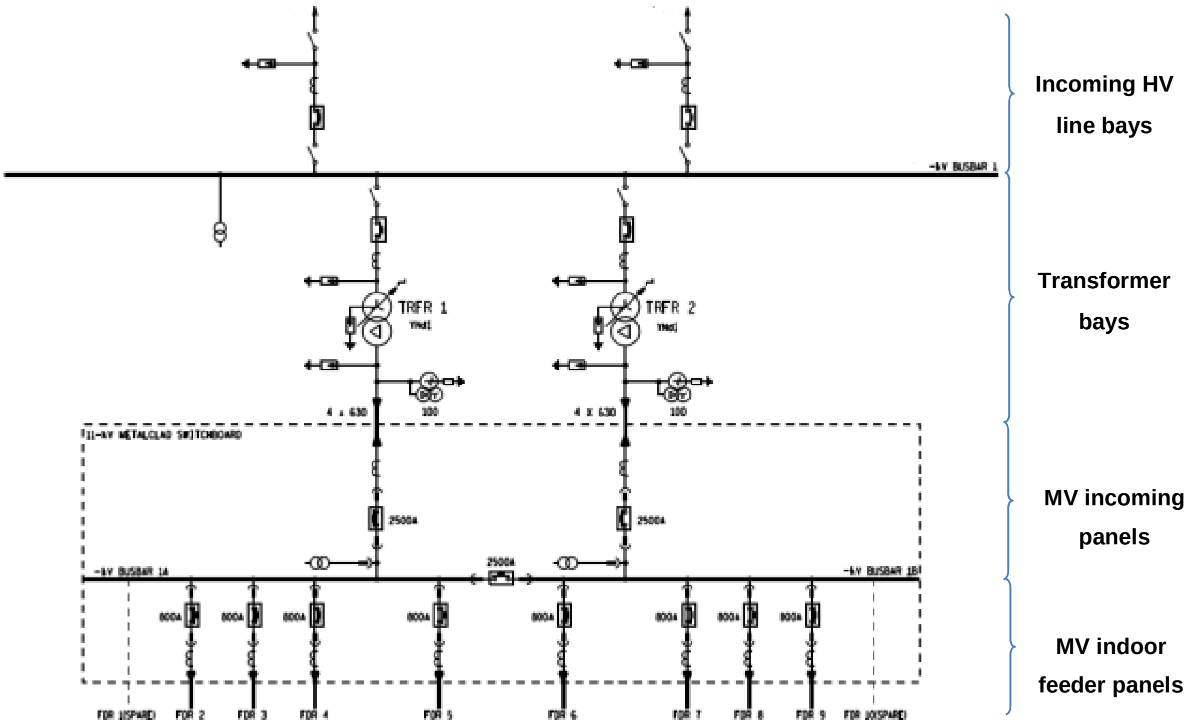


Figure 3-11. Indoor substation [46]

The difference in the above two general types are the distribution feeder components. The outdoor feeder bays require more civil and electrical components and the indoor feeder bays are all indoor panels compacted into a standard switch room [46].

The components that make up the substations above are used to derive the configurations to which DG may connect to. Several options may exist. This is dependent on the existing infrastructure in close proximity to the DG plant. As explained in this section, the configuration is voltage and DG magnitude dependent, therefore a need arises to establish a correlation between connecting voltages, network configuration type and DG magnitude for both MV and HV. Further, to complete this design guideline, costs attributed to each type should be considered as this is also an essential component of a financial justification model.

3.3.3 Component costing

In order to determine the costing for DG integration, the components required for the analysis have to be determined. By using the above information of the nature and structure of MV and HV networks, building blocks of these components is used to determine the engineering costs. The flowchart shown in figure 3-12 explains the process of design 3.

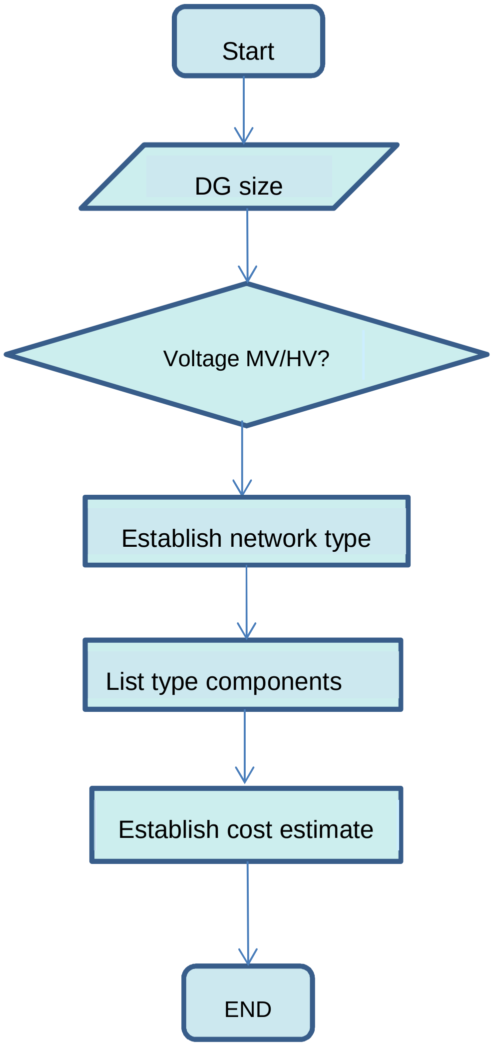


Figure 3-12. General process of design 3

The results of each design are discussed in chapter 4. The generic model for designs one and two were chosen to represent sub-sets of large practical network grids. DPL scripts as well as the relevant flowcharts were designed to produce results that can easily be adapted by the network planning engineer and utility. Design 3 guideline ties both design one and two together.

4 Results and Discussion

This chapter presents the results and discussion of the simulations performed on the test grids. Section 4.1 presents the results of using the amended Viterbi algorithm to establish a set of components to which connected DG control. Section 4.2 presents tabulated results of planning criteria under a common network scenario in which voltage instability of distribution busbars may result. Section 4.3 presents' four different network configurations for electrically integrating DG to existing utility infrastructure and quantifies in detail the cost viability of such a connection.

4.1 Results for design 1: DPL script execution and results in finding critical paths

The aim of this design was to calculate the critical path of the test grid of figure 4-4. In these results, a matrix is created with all the relevant busbars and short circuit current values. An example of a subset of this matrix is shown table 4-1. These results are then graphically (figures 4-1 to 4-4) shown where it is clear as to how cumulative generator fault currents summate to close proximity busbars.

The script initiates by firstly locating all machines and allows the user to adjust which machines are to be included in the analysis. This is important as in larger grids, the iterations become too long and data too much to analyse. Furthermore, the utility as mentioned previously, may have modelled transmission generators on that particular grid, which one may or may not include in the analysis.

The next step in the program is to *calculate the critical path* using the fault level of normal network configuration as base case and then calculating the injection contribution on that connected element by each machine, running during steady state conditions one after the other. This difference as defined earlier is the *variance parameter (VP).* The program starts executing with Machine 1 as the starting source node.

Table 4-1. Subset of fault level results for fault current contribution at each bus

Element	3 ph base	1 ph base	3 ph M1	1 ph M1	3 ph M2
11kV Bus 4	20.08	27.76	21.72	29.70	28.25
11kV Bus 3	21.24	31.86	22.84	34.16	33.03
Terminal 2	21.24	31.86	22.84	34.16	33.03
Terminal 1	21.24	31.86	22.84	34.16	33.03

132kV Bus 2	18.85	18.27	18.98	18.35	19.47
132kV Bus 1	25.00	26.46	25.12	26.54	25.62
132kV Bus 3	9.41	7.34	9.44	7.36	9.56

Two sets of results of adjusting the variance parameter is shown in the graphs of figures 4-1 to 4-4 below. With a variance of *2*, it can be seen that the summated contribution of each generator to a bus, results in three buses being selected. In figure 4-1, it shows that as each machine reaches steady state operation, the fault level increases from 20kA at *Bus 4* to 27kA. The final value of 27kA is reached when machine M4 comes into operation. In changing the variance parameter to 0 results in all eight buses being selected and each having a final value when machine (M4) is running.

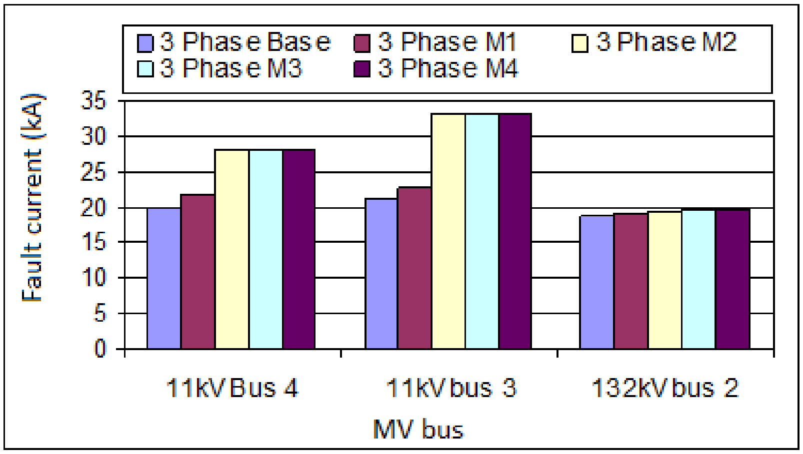


Figure 4-1. Three phase fault levels (Variance 2)

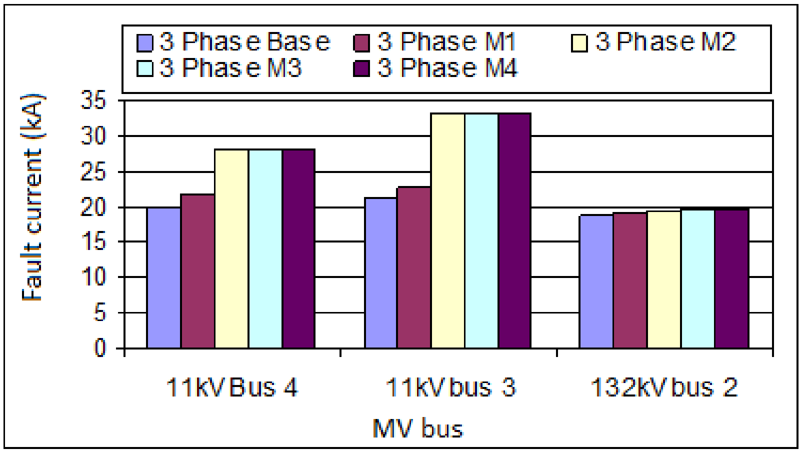


Figure 4-2. Single phase fault levels (Variance 2)

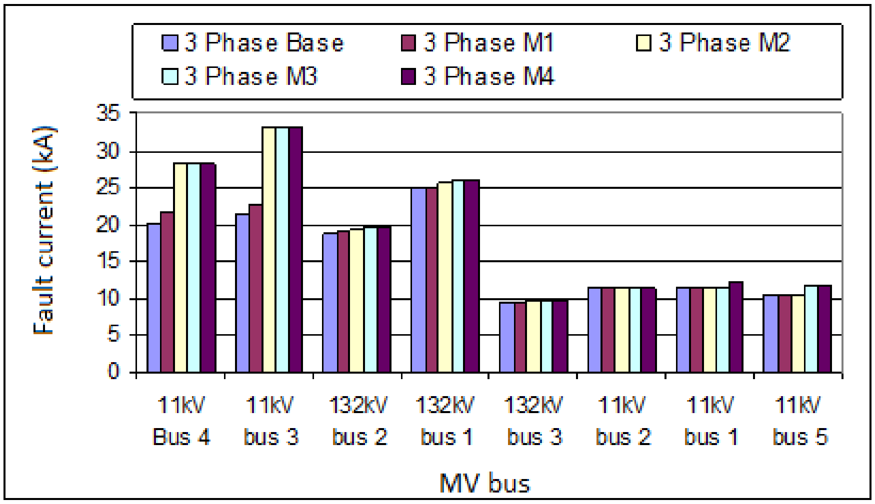


Figure 4-3. Three phase fault levels (Variance 0)

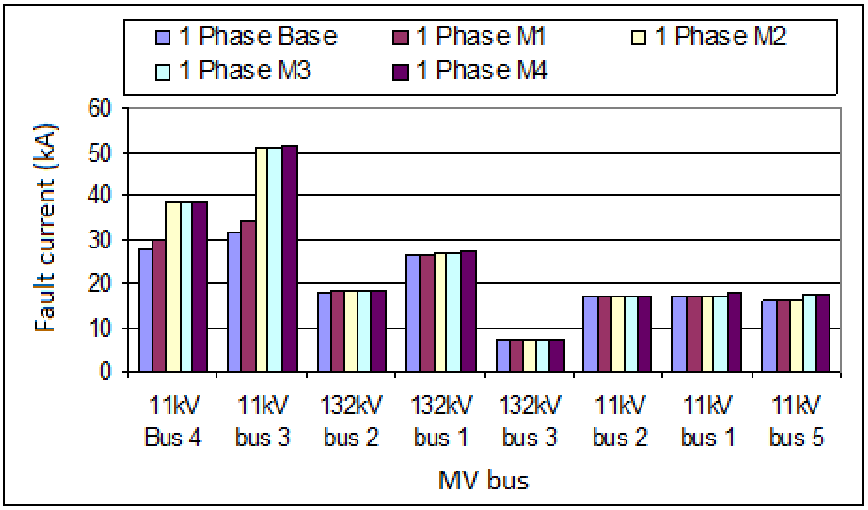
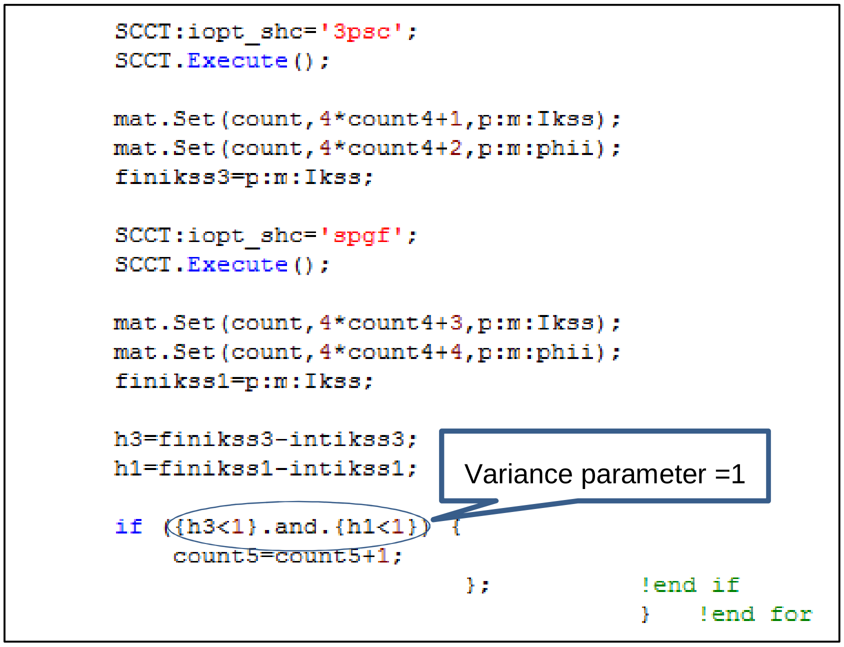


Figure 4-4. Single phase fault levels (Variance 0)

As the variance parameter (Vp) decreases (the difference in base case fault level from injected short circuit current), more HV electrical components are affected by the summated fault current injection. Changing this variance is shown in the screen dump of the DPL code in figure 4-5. It can also be seen from figures 4-1 to 4-4 that at some buses the fault current remains constant as more machines are turned on. This implies that the cumulative effect of three phase fault current from each connected machine at that specific bus is almost negligible as the difference is dependent on the set variance parameter.



```
SCCT:iopt_shc='3psc';
SCCT.Execute();

mat.Set(count,4*count4+1,p:m:Ikss);
mat.Set(count,4*count4+2,p:m:phii);
finikss3=p:m:Ikss;

SCCT:iopt_shc='spgf';
SCCT.Execute();

mat.Set(count,4*count4+3,p:m:Ikss);
mat.Set(count,4*count4+4,p:m:phii);
finikss1=p:m:Ikss;

h3=finikss3-intikss3;
h1=finikss1-intikss1;

if ({h3<1}.and.{h1<1}) {
    count5=count5+1;
                            };          !end if
                                        }    !end for
```

Variance parameter =1

Figure 4-5. Screen dump of DPL code showing Vp change

Once a set of relevant values are found, the critical path is located and the script then proceeds to complete a load flow analysis on the saved components of the path set. Figure 4-6 shows the path found in the test grid. The path includes the effects of all machines. The variance in this case, for illustrative purposes, was chosen to be 0.5. If the variance is chosen to be 0, then the result is that in the whole grid, the generator affects all components and the critical path includes all components as well. In strong network grids with adequate fault levels, the variance parameter should be approximated to 0 as the summation of the injected generator fault current and the network grid fault level may exceed equipment ratings and further network strengthening is required. If the network is weak, the injected generator fault current will strengthen that network and the accuracy of determining the critical path is determined by keeping the variance parameter as small as possible. In the KZN province, weaker distribution substations (approximately 60% of the total no. of substations) have a fault level range from 1 to 5kA [47] and typical MV equipment have a rating of +/- 10kA [46]. Therefore it can be concluded that for strong networks based on the above, that a Vp value of 0 should be used and for weaker networks, Vp values can range from 1 to 5. Values higher than this range would select no critical path and practically exceed equipment ratings. Once the critical path is found, power flow results can then be derived for sub-transmission lines and substation transformers. Load flow analysis is performed during peak and light loaded conditions. To illustrate this functionality, figure 4-7 shows loading of the cable interconnection (labelled in figure 4-6) during light and peak load conditions. Figure 4-8 shows the percentage losses on the sub-transmission 5km Kingbird type line [45] (labelled in figure 4-6) also during peak and light loaded conditions. This study can be extended to large grids and the identification of critical paths enables better planning from an investment and technical configuration perspective.

The components identified from the critical path require upgrades or new equipment to be installed but the steady state technical checks are only a part of a successful integration plan. The next section deals with criteria that prevent voltage instability of distribution busbars with multiple generators connected in close proximity.

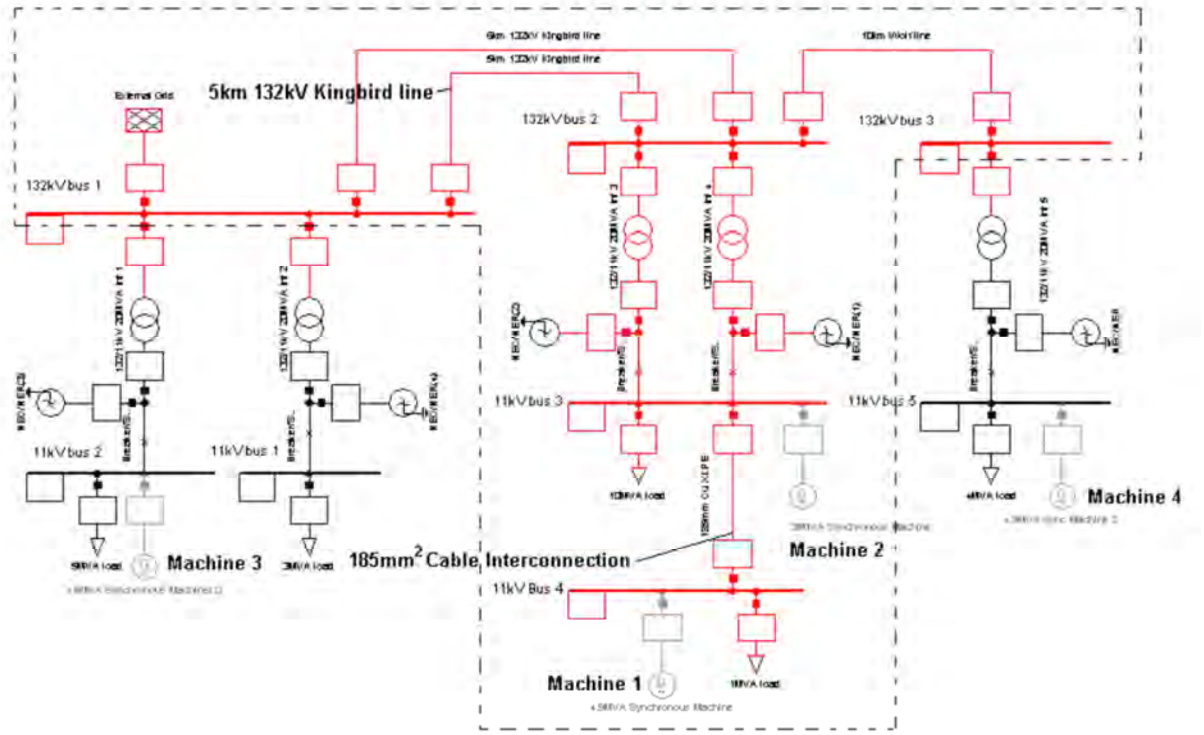


Figure 4-6. Study grid of design 1 showing critical path found (marked in red and blocked)

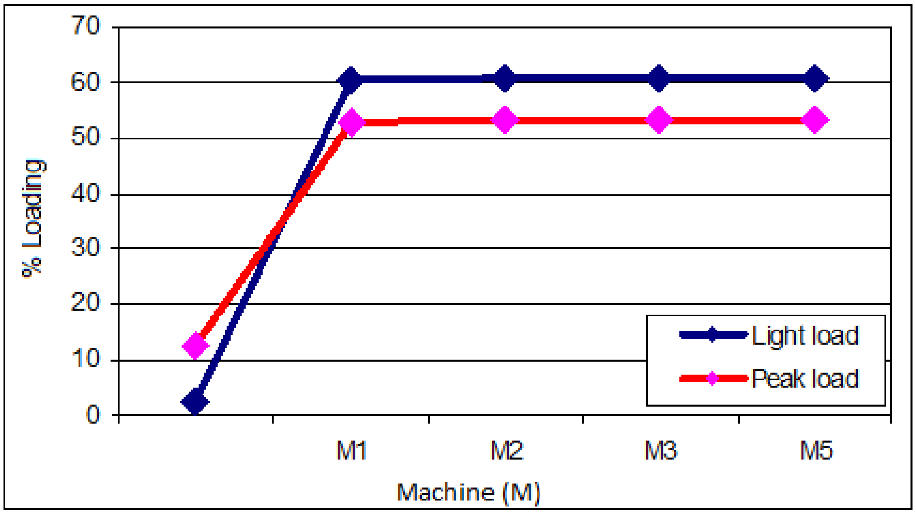


Figure 4-7. Graph analysing the % loading on the 185mm² cable interconnection at different levels of machine operation

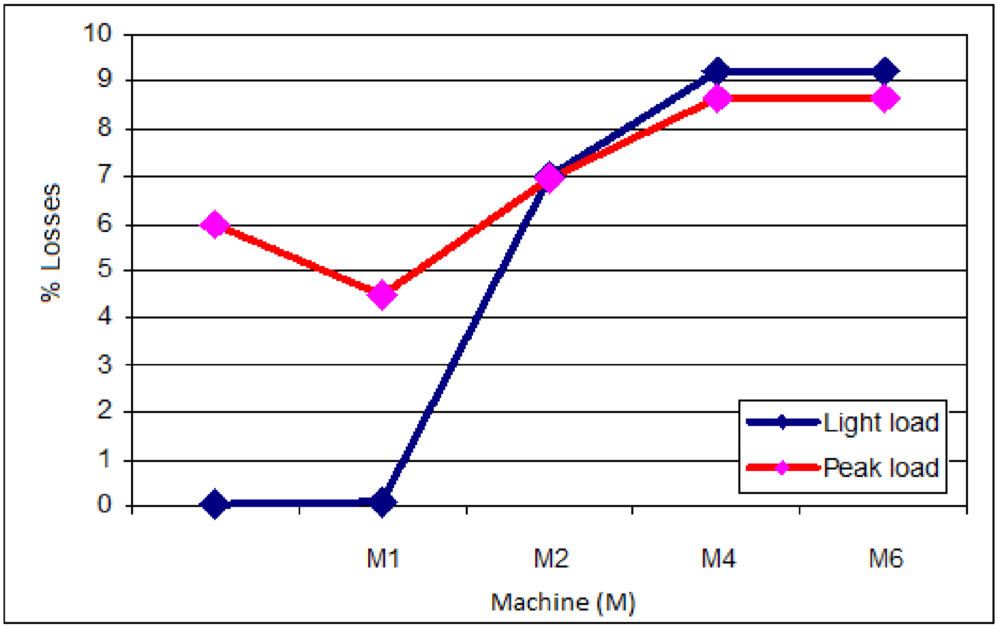


Figure 4-8. Graph analysing the % Losses on the 5km Kingbird line at different levels of machine operation

The test grid of figure 4-6 is practically a subset of a large network and the components chosen for analysis as in figure 4-7 and 4-8 are interconnecting lines to substations. Practically, a scenario may exist where in figure 4-7, the cable feed may overload on one or both loading conditions. This cable would then have to be replaced by a larger feed or an alternate solution in reconfiguring the network is required. This change in upstream impedance changes the dynamics of the power system and has to be re-modelled to be accounted for. Similarly in figure 4-8, losses on a particular network can be greatly reduced or increased and as such is quantified in terms of the cost factor. Connecting multiple DG units in a specific grid may increase the operational and maintenance cost of the network and thus makes the DG project not feasible.

Practically the utility’s network planning engineer should not choose the brute option as to maintain the upstream network impedance. A thevenin equivalent of upstream network can be deduced but more than one critical path may exist so an analysis of the entire network is therefore preferable. The DPL script structured in this design therefore enables the planning engineer to easily identify network elements that require attention when analysing multiple generators sharing common infrastructure. Figures 4-7 and 4-8 further identifies technical constraints of network elements in the critical path. The method of filtering through a large network maximises accuracy and is less time consuming.

4.2 Results for design 2: Grid Voltage Stability

The aim of this design was to calculate a ratio of network strength to generator fault current such that no instability occurs at relevant busbars (figure 3-5) at the loss of peak generation during peak load times. The results documented in this section provide a rule of thumb for three sub-sections of network strength range. For each network strength range, graphs (figures 4-13 to 4-15), a ratio of network strength to generator short circuit current is identifed and summarized in table 4-2.

With each changing value of the grid strength and machine injection, a sudden disconnection of one of the generators during peak load and reconnection within the critical clearing time, provide all relevant results. From the analysis, for the 1-5kA range, it is found that a standard deviation of less than 0.16 (shown in figure 4-9) implies that a stability point is reached on the connecting busbars, however, the busbar voltage is pulled down considerably. Figure 4-10 shows the cut-off point of a deviation greater than 0.16. The graphs shows that no voltage profile on eithe busbar settles and therefore affects the dynamics of the system.The second factor of voltage drop would contravene the quality of supply grid codes stipulated by the national regualtor [5] and is therefore the second deciding factor to the intended results.

One needs to note that this analysis is completed such that the critical clearing time is realistic and does not affect the results. For the remaining two fault level ranges, a cut-off point between stability and instability similar to the standard deviation results of range 1-5kA is also established. It is also shown that the graphs follow the same pattern and differ only slightly.

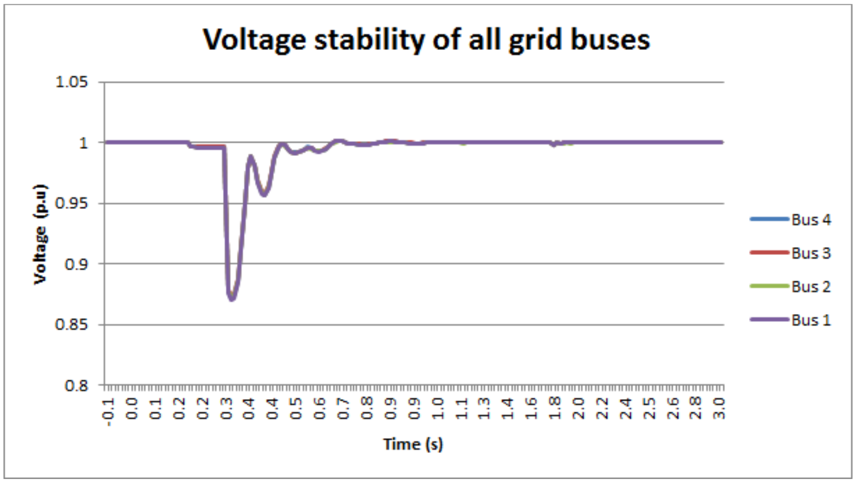


Figure 4-9. Standard deviation of (<) 0.16 showing stability reached for the 1-5kA range

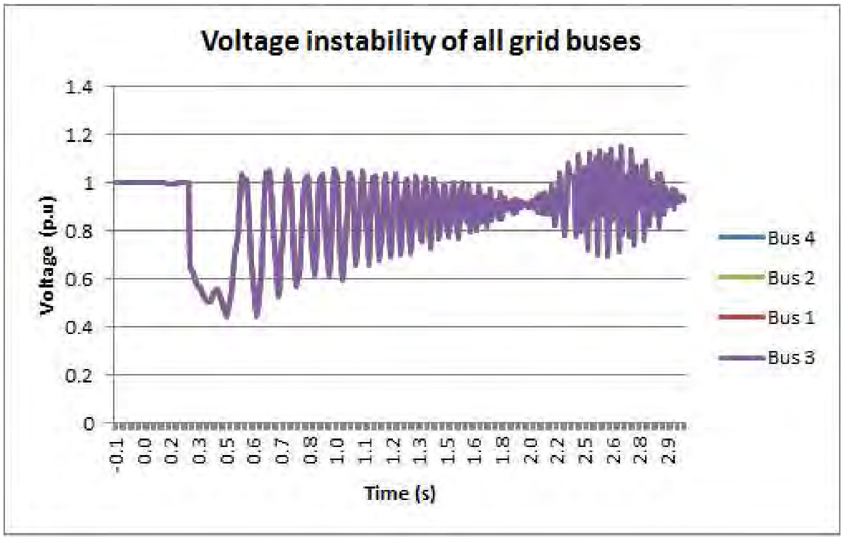


Figure 4-10. Standard deviation of (>) 0.16 showing instability for the 1-5kA range

To make the results are more generic, the fault levels at the connecting busbar of the disconnecting generator is analysed before and after the connection. This is done by opening *(result: base)* and closing *(result: close)* the breaker between the DG plant and utility grid and completing iterations of short circuit calculations. This provides a reference to work with. These values were compared to the sum of the grid value inputs (result: *Gsumg*) and was found that the conclusions arrived at are consistent for all three investigations. The first scenario of raw data output as per Digsilent Powerfactory is shown in Appendix A1. The raw data points describe the voltage plots at each bus on the disconnection event. The values of Grid 1 and Grid 2 determine the network strength in kA. The graph in figure 4-11 shows the plot of all buses for grid 1 = grid 2 = M =1. It can be seen that voltage stability is reached and poses no serious problem to the system, however the voltage dip is approximately 7%. Appendix A2 shows the raw data that corresponds to the graph shown in figure 4-12. Similarly, all scenarios as per table 4-2 are simulated and the raw data captured in excel.

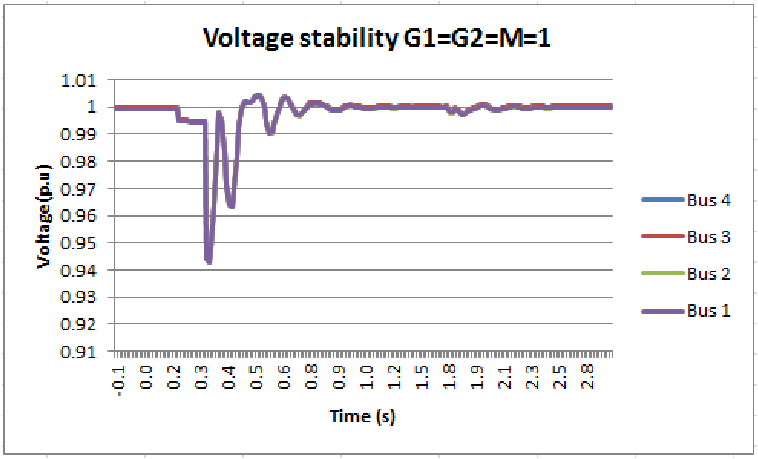


Figure 4-11. Voltage stability plots for Grid 1 =1, Grid 2 = 1 and M = 1

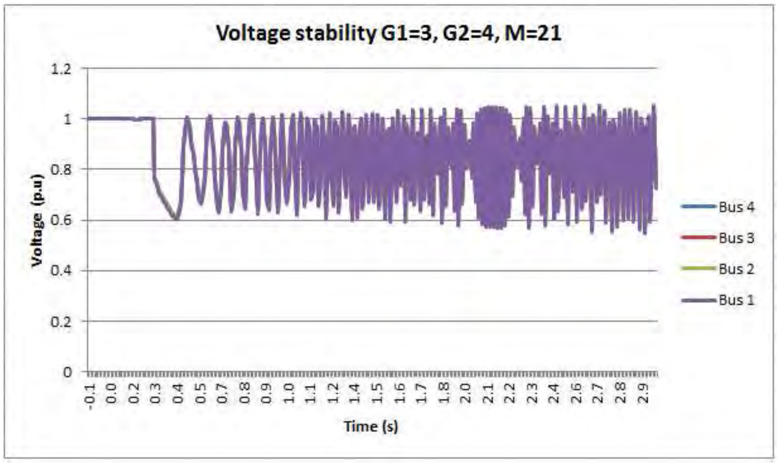


Figure 4-12. Voltage stability plots for Grid 1 =3, Grid 2 = 4 and M = 21

The raw data is analysed using visual basic coding [49]. The accepted and non-accepted values for the 1-5kA range are shown in appendix B1 and appendices B2 and B3, show the 4-10kA and the 10-15kA ranges respectively. Figure 4-13 plots the ratio of grid strength 1-5kA and machine strength with the limitation of volt drop not exceeding more than 5%. Similarly figure 4-14 and 4-15 show the resulted ratio for the 4-10kA and 10-15kA network scenario. The legend in each graph shows three sets of results. “3ph close/M” refers to the ratio of the three phase fault level of the grid with the generator to the injected current of the machine. “3ph base/M” refers to the ratio of the three phase fault level of the grid without the generator to the injected current of the machine and “Sumg/M” refers to the summation of the two grid value inputs to the injected current of the machine.

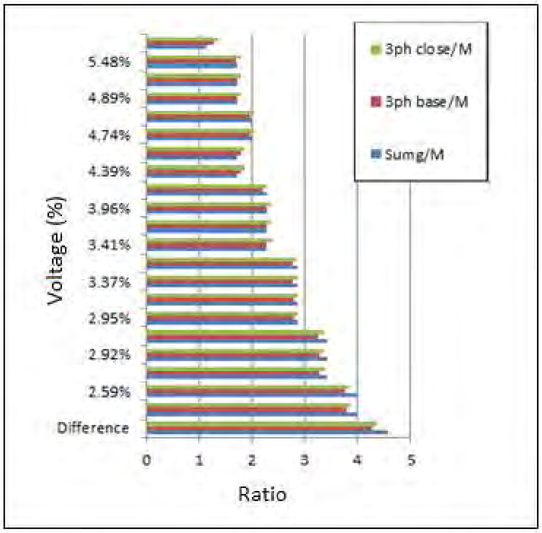


Figure 4-13. Ratio of 1-5kA network

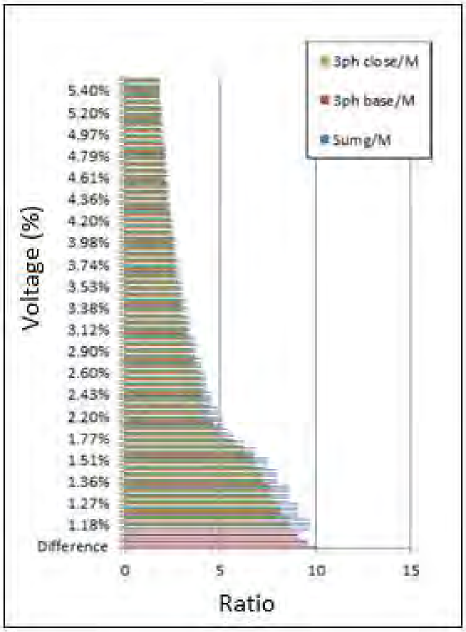


Figure 4-14. Ratio of 4-10kA network

Table 4-2 shows the summary of different network strengths, and grid to machine ratios found for a 3% and 5% voltage drop. Although the synchronous machines were analysed under voltage control mode, the effects of the disconnection of the any one of the single generators connected in a multi-machine scenario on the same HV electrical infrastructure, may cause drastic instability problems if not properly planned and analysed. Figure 4-16 shows the plot of busbar voltages with the complete disconnection of generator 1. It can be seen that voltage drops are minimal and no voltage instability scenario exists as expected.

Table 4-2. Summary of findings

Grid strength	3% Volt drop	5% Volt drop
1-5kA	2.9	1.71
4-10kA	3.6	2.06
10-15kA	3.7	2.12

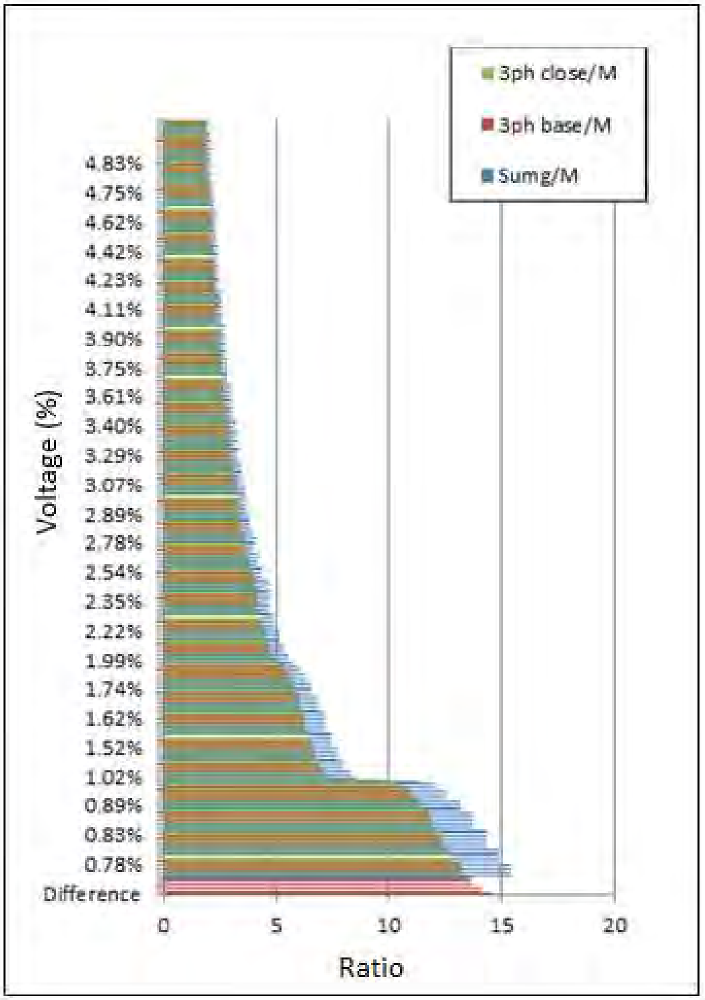


Figure 4-15. Ratio of 10-15kA network

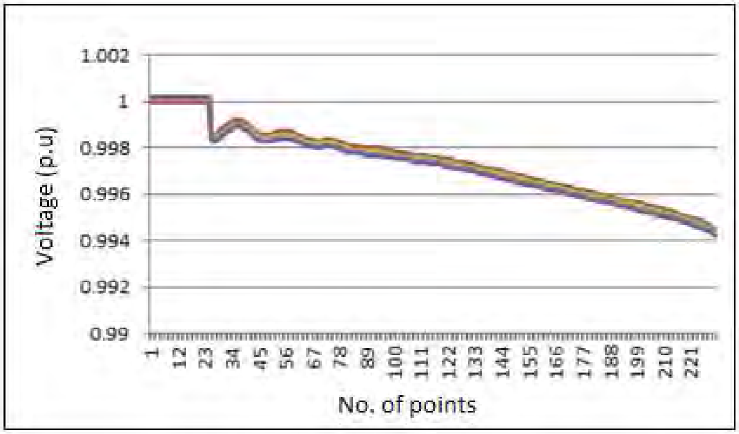


Figure 4-16. Complete disconnection of one generator in the closed system

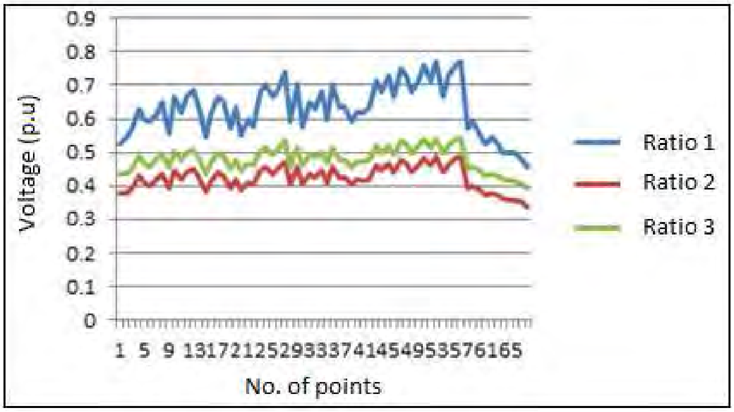


Figure 4-17. Grid to machine ratios for upstream system faults

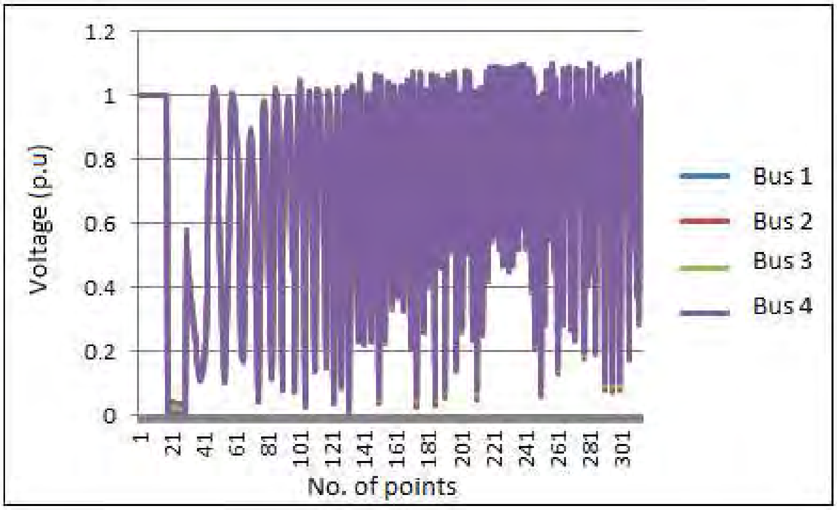


Figure 4-18. Voltage instability for ratios below 0.7

The second scenario considered to obtain similar sets of results can also further be divided into two. The first being an upstream three phase fault within the CCT (100ms) and a three phase fault on the connecting generator busbar. Once again, with the two network strengths controlling the model, one can analyse different network strengths that interact with different generator sizes preventing grid voltage instability. Figure 4-17 indicates the ratios established for the three phase faults scenario.

From figure 4-18, it can be seen that any value ratio below 0.7 of grid to machine strength renders busbar voltages unstable.The previous scenario is therefore considered a worse case event and the summary of results obtained in that study will therefore apply. It is further concluded that load to generation ratio plays an essential operational role and requires further research beyond the scope of this dissertation.

The summary of findings in table 4-2 derived from figures 4-13 to 4-15 can be explained as follows: If a network generator is to be connected to a network grid that has a network strength for e.g. 3kA, the proximity voltage busbars will not experience any voltage instability or voltage regulation problems at the loss of peak generation supplying peak load, provided that the kA value of the grid divided by the generator short circuit current (1.75kA) is of the ratio in table 4-2 of *1.71* or *3*. The planning engineer can use this as a rule of thumb where steady state studies satisfy the connection but voltage stability in a multi-machine scenario may become a deciding factor to a utility's development plans and or to the utility's renewable energy plans. The advantage of this analysis further enables cost effective infrastructure planning, utility capital project prioritization and the creation of entry points to improve network performance.

4.3 Results for design 3: Network Configuration Types

In this design, a guideline was required in physically connecting the distributed generator to the grid. The results for establishing network connection types (figures 4-19 to 4-22) are in the order of medium to high voltage distribution networks. Each configuration is a point of integration and is based on current practices. The next step is to determine possible DG size and is shown in table 4-3. Explanation's governing the table outputs is further explained as well as two guideline examples illustrating the usage of the identified tables for cost estimation, is also documented.

4.3.1 Connection types

Four types of connections have been identified to the various networks ranging from MV to HV. These four types show where the DG is connected wrt the utility network.

The PGC, defined as the *point of generator connection* [6], is the actual connection of the generator to the network or step-up generating transformer. The developer is required to but not compelled to ensure that the protection requirements in [6] are adhered to. At the PUC, *point of utility connection*, is defined as that point to which the generating plant connects to the utility grid. It is here in which the utility has full control and all the protection requirements in [6] are applied.

As explained further in this section (4.3.2 - 4.3.4) of how to use the four connection types to connect to distributed generators, it must be noted that there are various upstream technical issues that are required to be dealt with. The first is the relevant protection types and the second is any upstream strengthening or refurbishment that is required. Matched protection schemes and the disabling of reverse power protection on upstream transformation (if needs be) are some of the protection issues that need consideration. Additional sub-transmission or transmission lines/transformation may also be required. All of the above are the main components in technically connecting DG to the utility grid.

Type 1 connection**:** The generator is directly connected to an overhead or cable network. The electrical single line diagram is illustrated in figure 4-19.

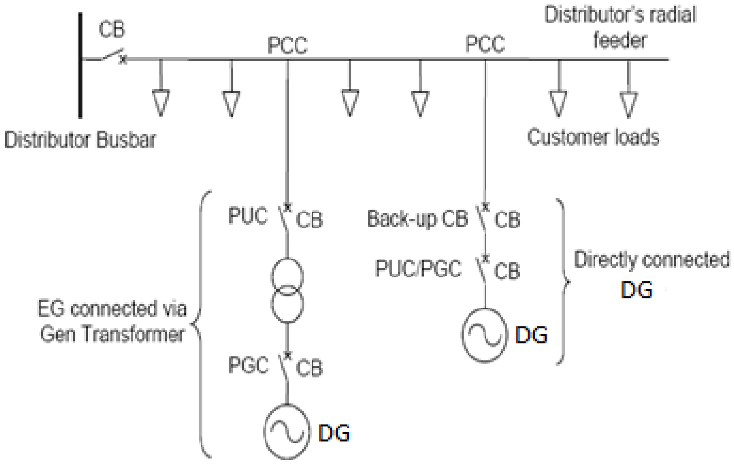


Figure 4-19. Overhead/cable direct DG connection

Type 2 connection**:** The generator is directly connected to an MV (11kV, 22kV or 33kV feeder bay). The electrical single line diagram is illustrated in figure 4-20.

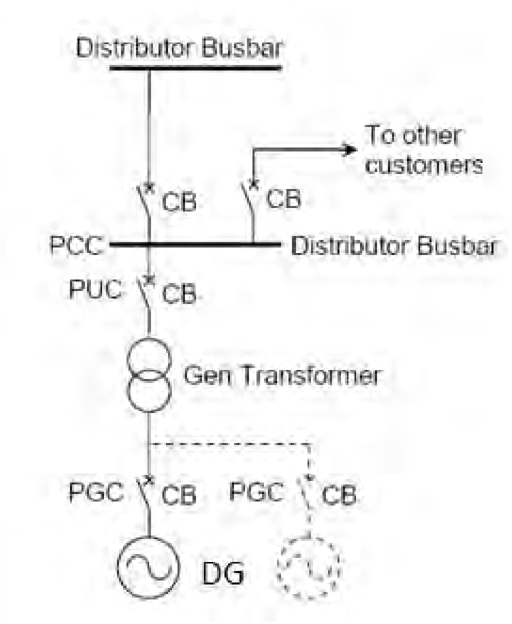


Figure 4-20. Direct Distribution feeder bay DG connection

Type 3 connection**:** The generator is directly connected to an HV (<=33kV feeder bay). The electrical single line diagram is illustrated in figure 4-21.

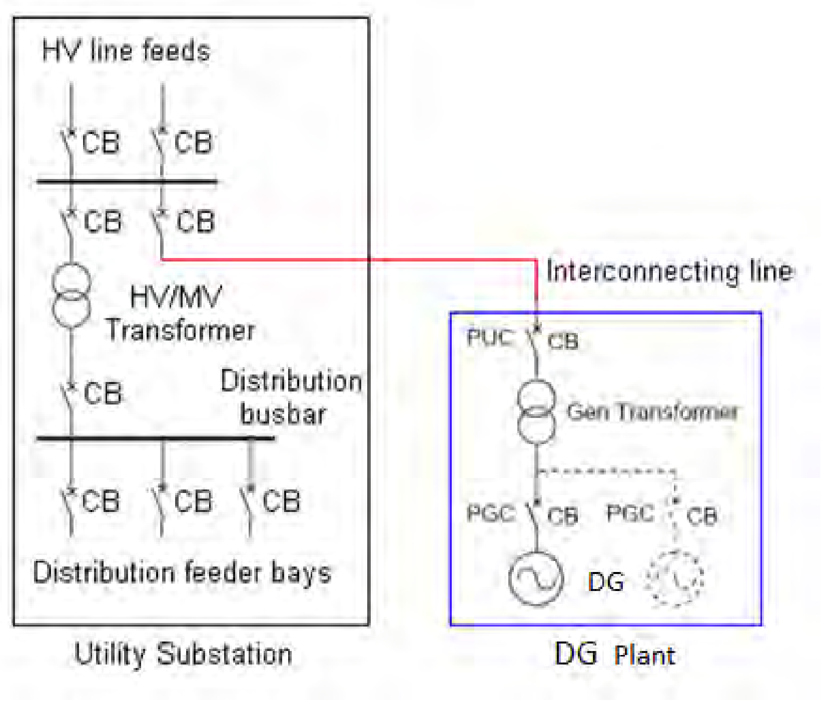


Figure 4-21. DG plant and Utility substation HV connection

Type 3 connection applies to any DG plant that is required to connect to a higher utility voltage because of the large magnitude of generation. The utility substation may be a

Transmission or Distribution substation, depending on the connecting voltage best suited for the project.

Type 4 connection**:** The generator is connected via a loop-in-loop-out configuration off the proximity HV line. Figure 4-22 shows the integration of this line to the power station (P/S) HV busbar. A HV switch arrangement demarcates the utility equipment from the P/S substation equipment. HV Transformer breakers are defined as the point of utility connection and is that this point to which the P/S will again be disconnected on the protection requirements stipulated in the utility interconnection standard [6]. The interconnecting cable as per [6] is the responsibility of the DG plant.

Table 4-3 indicates the proposed type of configuration to be used for different sizes of generating plants. DG sizes may have one or more connection types depending on the proximity to existing electrical infrastructure. When more than one connection type exists, a dedicated connecting point is the *preferred* one, if financially feasible to the developer.

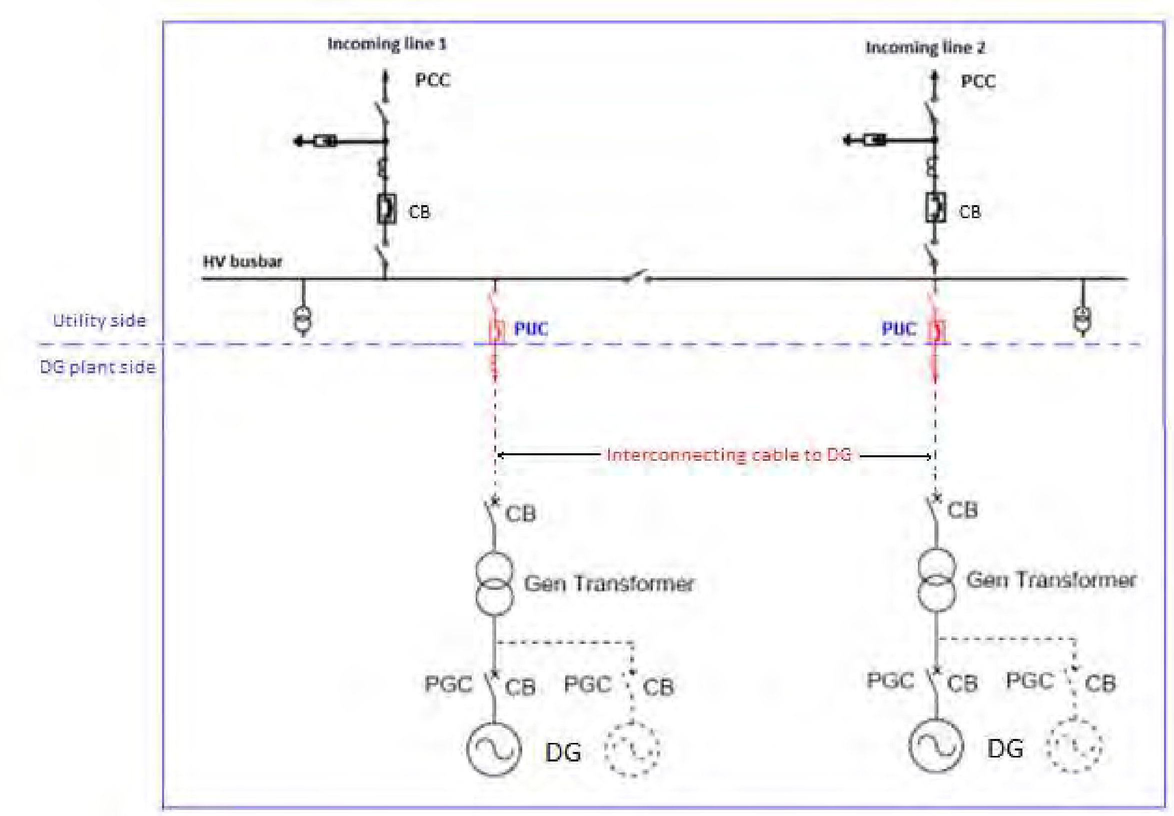


Figure 4-22. DG plant and Utility HV line loop-in-loop-out connection

Table 4-3. Proposed DG sizes and Type configurations

Connecting Voltage	Type 1	Type 2	Type 3	Type 4
11kV	< 2.5MVA	< 13MVA	N/A	N/A
22kV	< 5MVA	< 27MVA	N/A	N/A
33kV	N/A	N/A	< 28MVA	< 28MVA
33kV> & <88kV	N/A	N/A	< 56MVA	< 56MVA
88kV	N/A	N/A	< 75MVA	< 75MVA
132kV	N/A	N/A	< 112MVA	< 112MVA

4.3.2 Analysis of generator sizes and connection types in table 4-3

4.3.2.1 Connecting voltage: 11kV and 22kV

A direct connection at 11/22kV defined by type 1: The limit of 2.5MVA at 11kV and 5MVA at 22kV is based on the most commonly used conductor size of Fox (rated 148A) and within 90% of its rating. *A direct connection at 11/22kV defined by type 2*: The limit of 13MVA at 11kV and 27MVA at 22kV is based on the most commonly used indoor/outdoor breaker size of 800A and within 90% of its rating.

Both connection types require: Fault levels, voltage rise and RVC % change have to be accounted for. Export power limited by conductor or cable and short circuit ratings of <3kA and <25kA respectively. See table 4-4.

4.3.2.2 Connecting voltage: 33kV-132kV

The limits defined in table 4-3 above are calculated by the using the source conductor feeder rating as the constraint. The most commonly strung conductor on high voltage lines are Wolf and Chicadee [45]. Wolf conductor (rated at 548A) and within 90% of its rating, was selected as the worst case option.

All the above connection types require: Fault levels, voltage rise and RVC % have to be accounted for. Export power limited by conductor and/or short circuit ratings of <40kA respectively. See table 4-4.

4.3.3 Cost estimation and equipment specification

From the design specifications above, the following cost estimates (tables 4-4 to 4-7) are assigned to the relevant connecting bays/points. All cost estimates are derived from various costing tools that are used in the utility network planning and engineering design area.

4.3.3.1 Feeder bays and line bays

Table 4-4. Feeder bay cost estimates

	Line bays	Feeder bays
Voltages	88kV,132kV	11kV,22kV,33kV
Breakers sizes	3150A	800A-2500A[1]
Fault rating	40kA[2]	25kA[1],20kA[2]
Est Costs	88kV: R2.7mil, 132kV: R3.3mil	11kV: R1.5mil, 22kV: R1.7mil , 33kV: R2mil

[1]Indoor, [2]Outdoor

4.3.3.2 Transformer bays: Type: YNd1, OLTC, 31mm/kV

Table 4-5. Transformer bay cost estimates

Voltage Ratios	Trfr size	Cost
132/22-11kV	10MVA	R8.6mil
132-88/33-22-11kV	20MVA	R11mil
132/33-22-11kV, 88/33kV	40MVA	R14.5mil
132/88-33-22kV, 88/33kV	80MVA	R16.5mil

4.3.3.3 Generic substation costs (HV / MV)

Table 4-6. Substation cost estimates

Voltage Ratios	Trfr size	Cost
132/22-11kV	10MVA	R24-29mil
132-88/33-22-11kV	20MVA	R28-32mil
132/33-22-11kV, 88/33kV	40MVA	R38-40mil
132/88-33-22kV, 88/33kV	80MVA	R44-52mil

4.3.3.4 Line type cost estimates:

Table 4-7. Line type cost estimates

Voltage Ratios	Cost
11/22kV Hare	R200k/km
88/132kV Hare	R1,2mil/km
132kV Wolf	R1,3mil/km
11/22kV Chicadee	R280k/km
88/132kV Chicadee	R1,3mil/km
132kV Rail	R1,9mil/km
132kV Kingbird	R1,5mil/km

4.3.4 Type with cost estimate summary:

Type 1: If no line or transformer upgrade is required then the only cost is for PUC protection, metering and other control instrumentation i.e. R800k.

If line or transformer upgrade is required then the cost is for PUC protection, metering and other control instrumentation (R800k) as well as the cost estimates in table 4-5 and 4-7.

Type 2: If no line or transformer upgrade is required then the costs are for PUC protection, metering, other control instrumentation and the relevant bay cost: (R500k) + MV bay cost as in table 4-4.

If line and/or transformer upgrade is required then the cost is for PUC protection, metering, other control instrumentation (R500k), relevant bay cost in table 4-4 as well as the cost estimates in table 4-5 and 4-7.

Type 3: If no line or transformer upgrade is required then the costs are for PUC protection, metering, other control instrumentation and the relevant bay cost: (R800k) + HV bay cost as in table 4-4.

If line and/or transformer upgrade is required then the cost is for PUC protection, metering, other control instrumentation (R800k), relevant bay cost in table 4-4 as well as the cost estimates in 4-5 and 4-7.

Type 4: The costs are for PUC protection, metering, other control instrumentation and a HV switch station cost: (R10mil).

It must be noted that further analysis of upstream equipment is required to be analysed and telecommunication must be installed or checked for visibility between sub-stations. Optic fibre also forms a component of the costing. These are additional costs. For example in all the above type configurations, if fibre is required upstream for protection communication then the cost estimate is approximately R180/m.

4.3.5 Implementation of the above estimates and type configurations

4.3.5.1 Consider a developer establishing a 9MVA plant in the location shown in figure 4-23. The substation in close proximity is called Umlaas Rd S/S and has a current peak loading of 7MVA, an average light load of 3MVA and an installed capacity of 10MVA. From table 4-3, the suited option would be *type 2* at 11kV. Additional cost 1 would be the increase in capacity as the sum total of the light load and generating load exceeds the installed capacity. Referring to table 4-5, the transformer bay costs for a 20MVA transformer would be R11mil. Additional cost 2 would be choosing a suited line type; 9MVA at 11kV is 472A. From figure 2-24, the chosen conductor is Chicadee and from table 4-7, the cost would be R140k for 500m as per figure 4-23. Therefore the total cost for this connection (assuming no upstream upgrades are required) is as follows:

(Protection and other instrumentation + feeder bay + transformer bay + line cost) =

R500k + R1.5mil + R11mil + R140k = **R13.1mil**

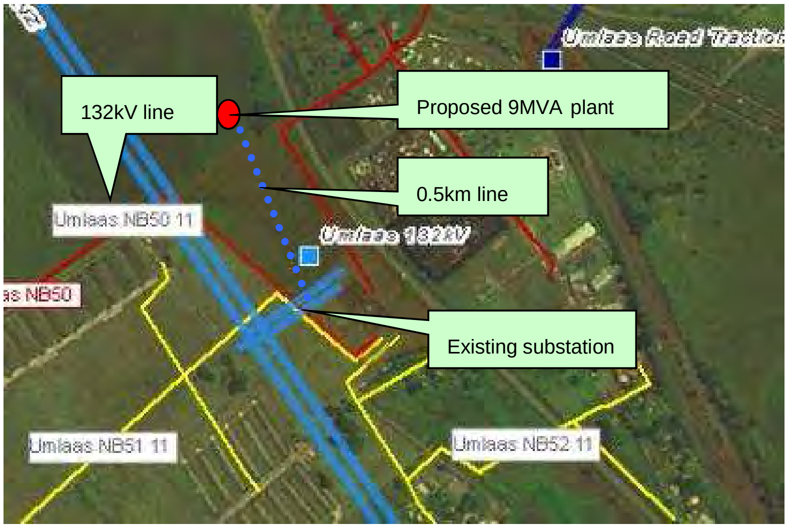


Figure 4-23. Power station location

4.3.5.2 Consider a developer establishing an 80MW plant in the location shown in figure 4-24. The infrastructure in close proximity is the 132kV Kingbird line and has a current peak loading of 50MVA, an average light load of 35MVA and an installed capacity of 195MVA at

70 degrees. From table 4-3, the suited option would be a *type 4 configuration* at 132kV. The total cost is therefore **R10mil** excluding fixed connection charges and any upstream strengthening or telecoms installation. Typically with Kingbird at 132kV, there are no technical issues at connecting DG other than the current carrying capacity, which in this case is not applicable due to the relatively small DG size.

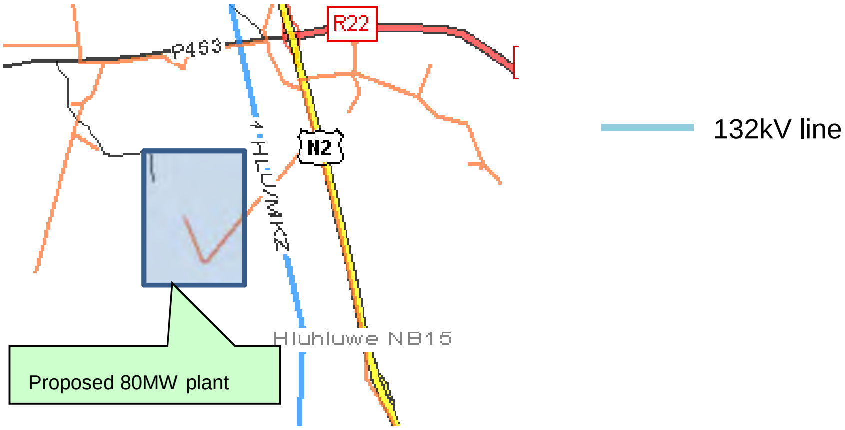


Figure 4-24. Power station location

The results compiled in the above guideline not only enable the utility planner but also a proposed developer in assessing an integration connection and cost of a particular energy project. The first step is to choose the type connection from table 4-3 based on generator size and network voltage. Once the planner maps out the proposed plant to the type configuration, a cost estimate can easily be created following the sequential steps as shown in section 4.3.4. This method is cost effective, time saving and fairly adequate as an input to a high level project financial feasibility study.

5 Case Study: Optimal Allocation of PV

Solar density mapping, over a time period, provides a quantifiable indication to renewable energy developers, feasible locations for the development of solar energy facilities. This information is beneficial to the utility in that electrical infrastructure that exists in the proximity of these locations can be assessed technically thus enabling a suitable integration point for the energy facility. This case study establishes a correlation between solar density maps and provides viable power output locations. This strategy is then expanded to provide a grid capacity connection assessment for a specific region in South Africa and therefore meets objective 4 of chapter 1.

With already established electrical networks in a specific area and the probability that a certain amount of generation may or may not inject to the proximity infrastructure, a mechanism is required to provide some control on random connection points. The simulation results for the study area concerned, quantifies a bandwidth within technical limitations to which PV sources can be connected.

The objectives of this study is to firstly establish photovoltaic (PV installations) *focus areas* within the chosen region, provide an indication of *MW output*, provide a high level analysis of the proximity of Distribution substations to these areas by *technical integration assessment* (sterilization and optimal allocation) and providing a *bandwidth* in MW's for that specific area.

5.1 Solar density maps and MW correlation of study area

Figure 5-1 shows the average annual solar irradiance of South Africa measured in kWh/m^2 [51].This mapping is updated to 2012 and is merged with the utility's Distribution networks in the chosen area of study as shown in figure 5-2. ESRI [50] has worked on compiling datasets identifying areas demarcated into polygons of viable PV installations in the area as shown in figure 5-3. A minimum of 10 hectares (10000sqm) per polygon represents these viable potential installations. Three clusters are identified as zone 1 to zone 3. A closer view of these zones is shown in figures 5-4 to 5-6.

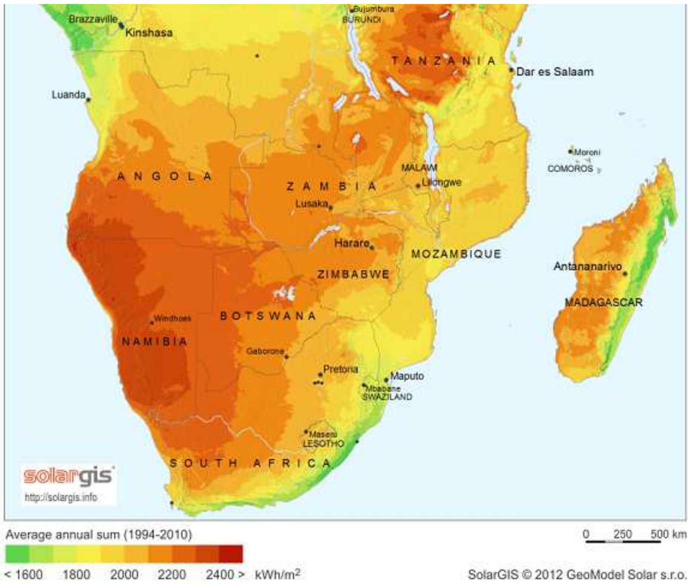


Figure 5-1. SolarGis Irradiance average annual sum levels up to 2012 [51]

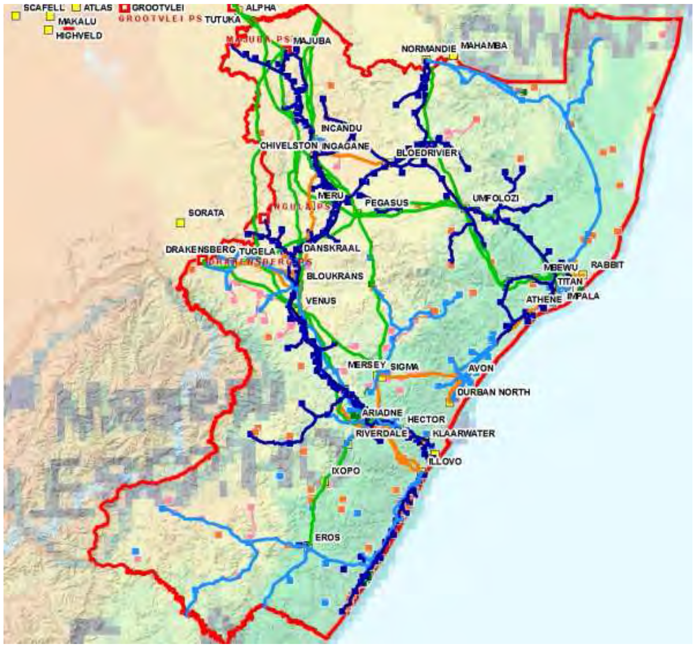


Figure 5-2. Electrical networks merged into the solar irradiance mapping of figure 5-1

In order to estimate the amount of power that the identified sites can produce, the following assumptions can be made:

- The average solar irradiance varies between 2000-2200kWh/m2 (figure 5-1)
- 2000kWh/m²→(2000x10000)kW.[8760h=1year]/8760.[10000m²=1ha] = 2283kW.year/ha = 2.2MW / ha/year
- For a 1ha site, the power output can be estimated to be:

  - 2.2MW per ha x 0.75 (losses) x 0.4 (efficiency.)
  - 0.6678MW per ha – *0.75MW per ha*

- Assuming 70-75% land usage, a **10ha** site, would imply that approximately **5MW** can be produced.

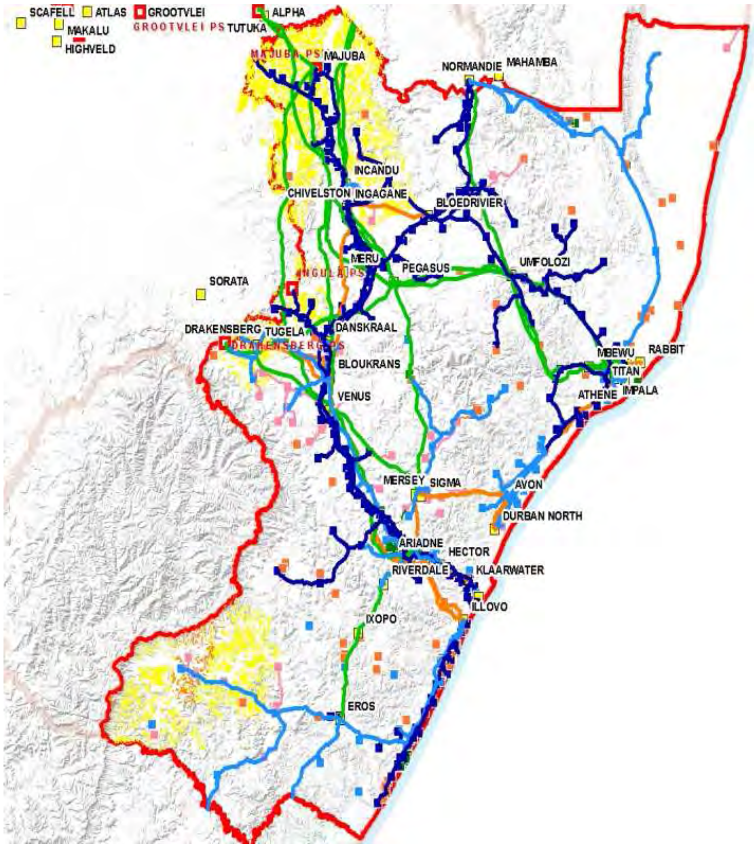


Figure 5-3. ESRI datasets showing viable PV sites throughout the study area

Figures 5-4 to 5-6 also show what distribution substations are in the proximity of the PV viable sites. These sites prove to be significant to PV developers as the upfront identified attributes are key inputs into project economic financial models, making them much more feasible PV projects.

Table 5-1 indicates the results of quantifying the viable polygons to MW output. It can be seen that a potential of **392GW** of PV power can be generated.

Table 5-1. Summary of polygon counts from datasets and MW output correlation

	Count	Min MW	Max MW	Sum MW
Figure 5-4	Zone 3			
Right Polygon	434	5	2,719	93,826
Left Polygon	408	5	5,898	137,877
Figure 5-5	Zone 2			
Upper Polygon	121	5	3,924	22,628
Lower Polygon	204	5	2,922	27,639
Figure 5-6	Zone 1			
Upper Polygon	877	5	6,348	74,269
Lower Polygon	439	5	5,495	36,677
Summation of Potential PV in study area				**392,916**

5.2 Study and analysis

From the above spatial analysis, it is clear that the magnitude of potential of PV installation far exceeds existing infrastructure injection capabilities. From figures 5-4 to 5-6, it is possible that a certain amount of PV generation can be connected to the utility grid. Upon connection, the technical limitations mentioned in the previous chapters have to be adhered to. The above three zones were analysed to provide an indication of the maximum amount of PV generation power that can be connected to existing infrastructure in that specific zone.

DIgSILENT programming language (DPL) is used for the technical analysis. All three zones are modelled in DIgSILENT as a joint grid that maps out the entire study region infrastructure (excluding medium voltage to low voltage). By controlling the integration of PV modules within the above grid, provides realistic results that may be applied as a rule of thumb in assessing PV integration in the study area.

The DPL script in each analysis starts off by providing base case results as a first pass, i.e. with no connected generation. Thereafter, PV modules (type data: 0.5MVA, 0.95pf, 0.4kV) are connected to each busbar and results recorded at each load flow and short circuit condition.

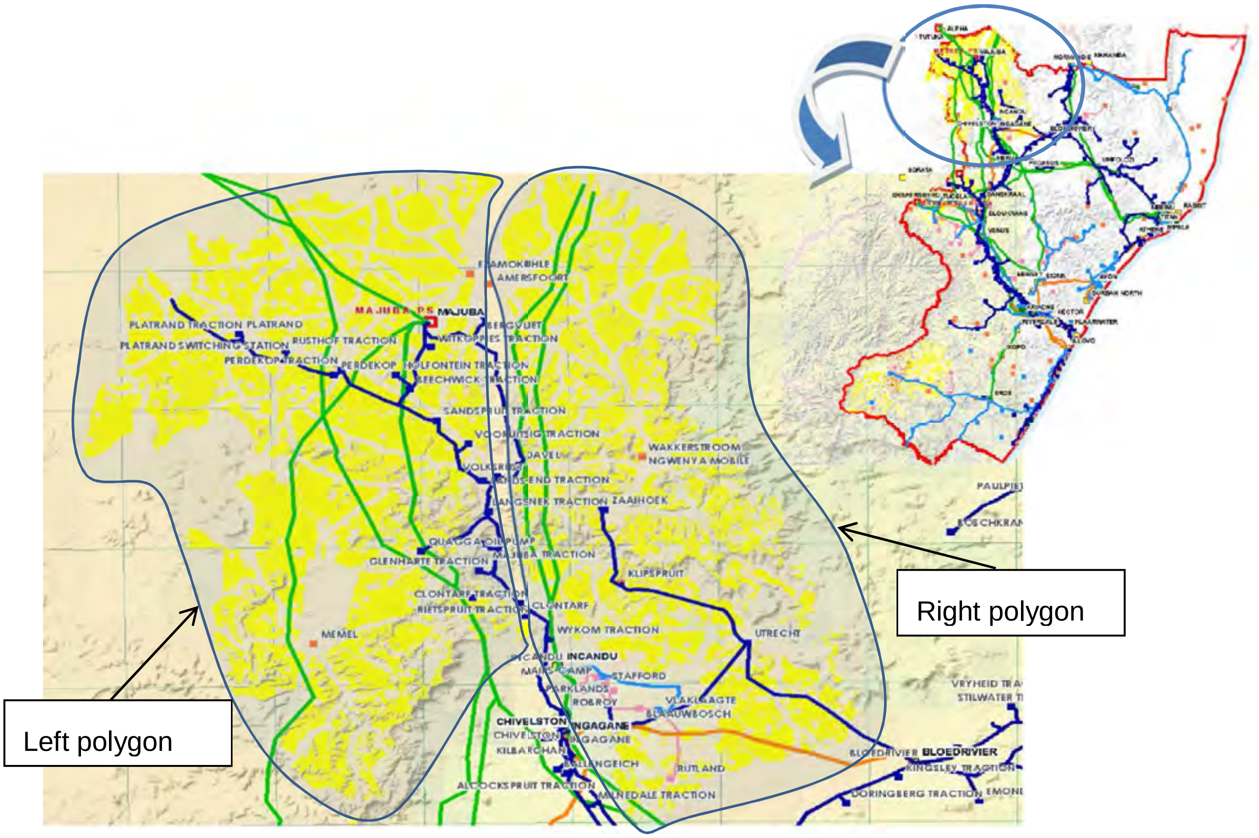


Figure 5-4. ESRI datasets showing viable PV sites throughout Zone 3

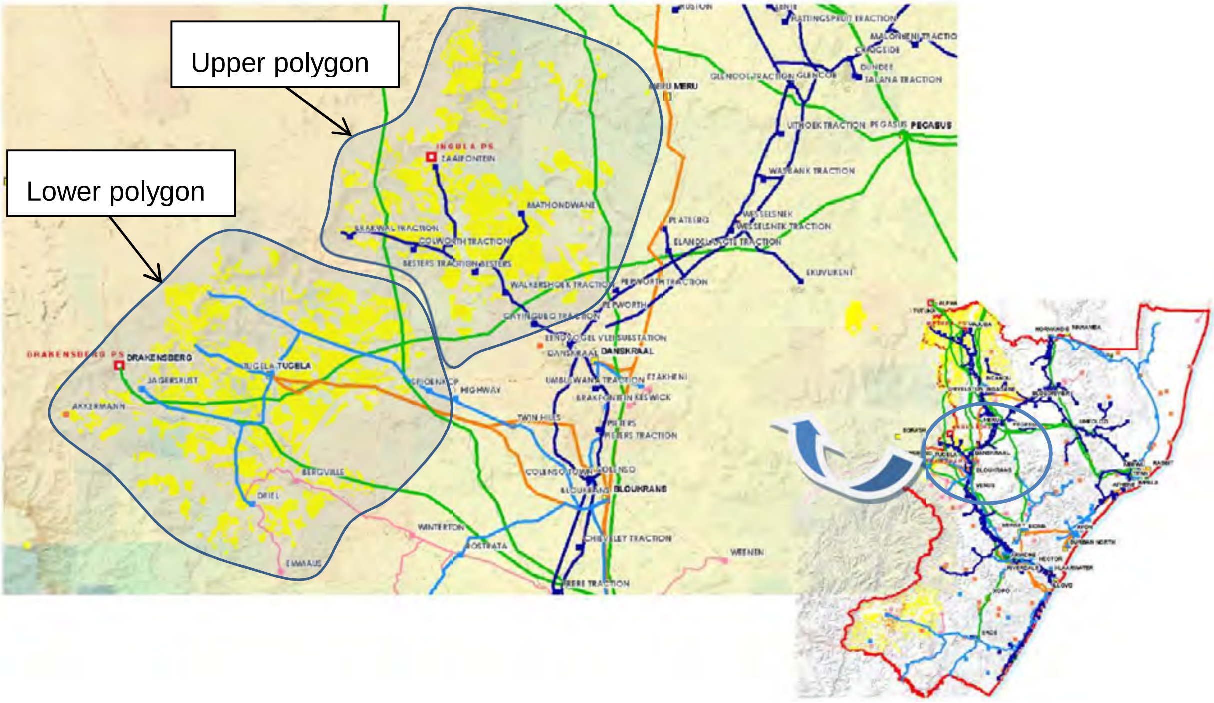


Figure 5-5. ESRI datasets showing viable PV sites throughout Zone 2

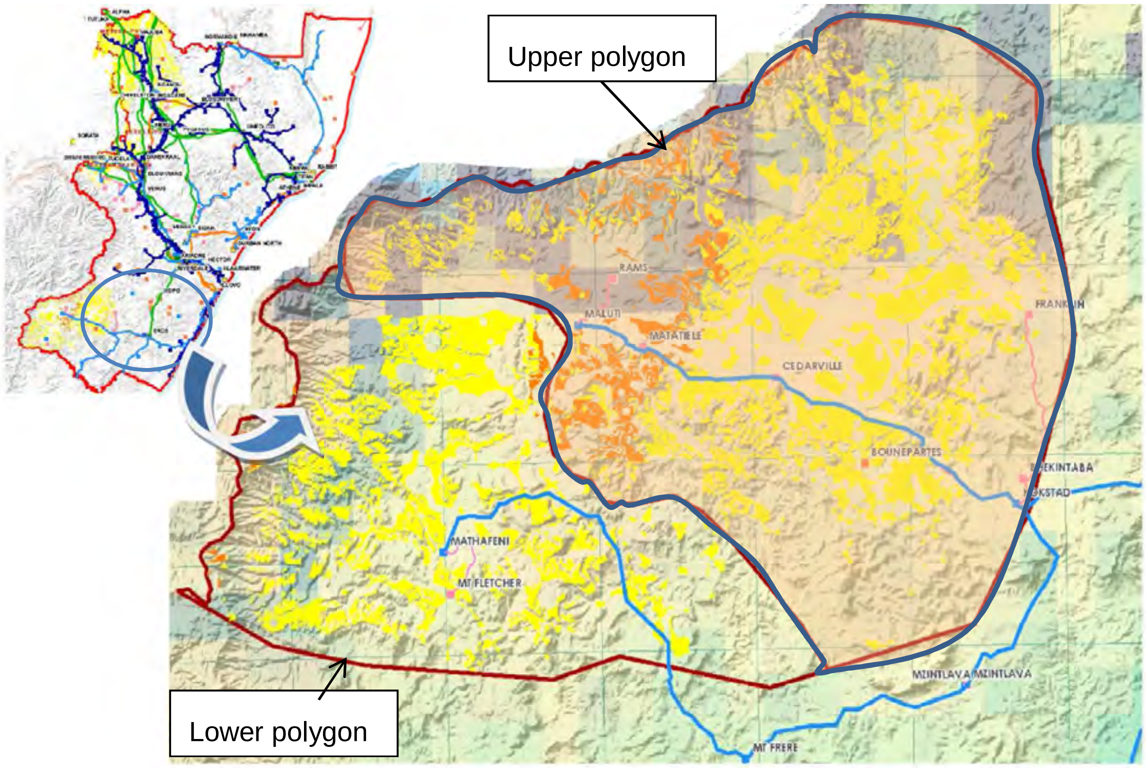


Figure 5-6. ESRI datasets showing viable PV sites throughout Zone 1

The relevant connecting busbars in Zone 1 is shown in table 5-2. Due to the relative weak and connecting voltage of zone 1, a range of values [1..5MW] of PV farms were chosen for the analysis. In executing the DPL script for this zone, PV plants of 5MW are connected in turn to each busbar of table 5-2 and this resulted in the fault level contributions as per figure 5-7. The fault current from each PV plant is modelled as a static generator using 1.2 times the power rating of the PV plant according to [44] and [5]. The brute force algorithm discussed previously in the thesis is used here (part A of section 3.1, chapter 3). Each graph in figure 5-7 is the cumulative contribution of fault current as each 5MW PV farm connects to each busbar in zone 1.These fault levels are within standard equipment ratings. This would imply that the maximum PV power (zone 1) that can connect to any Distribution voltage busbar is only dependent on the voltage rise and RVC studies.

Table 5-2. Affected busbars in the analysis of Zone 1

Zone 1 (15 selected busbars)		
BUS A-11kV BUSBAR	BUS F-33kV BUSBAR	BUS G-22kV BUSBAR
BUS B-11kV BUSBAR	BUS G-33kV BUSBAR	BUS E-33kV BUSBAR 1
BUS C-11kV BUSBAR 1	BUS F-33kV BUSBAR	BUS C-33kV BUSBAR
BUS A-22kV BUSBAR	BUS D-33kV BUSBAR	BUS C-22kV BUSAR
BUS D-22kV BUSBAR	BUS A-33kV BUSBAR	BUS B-33kV BUSBAR

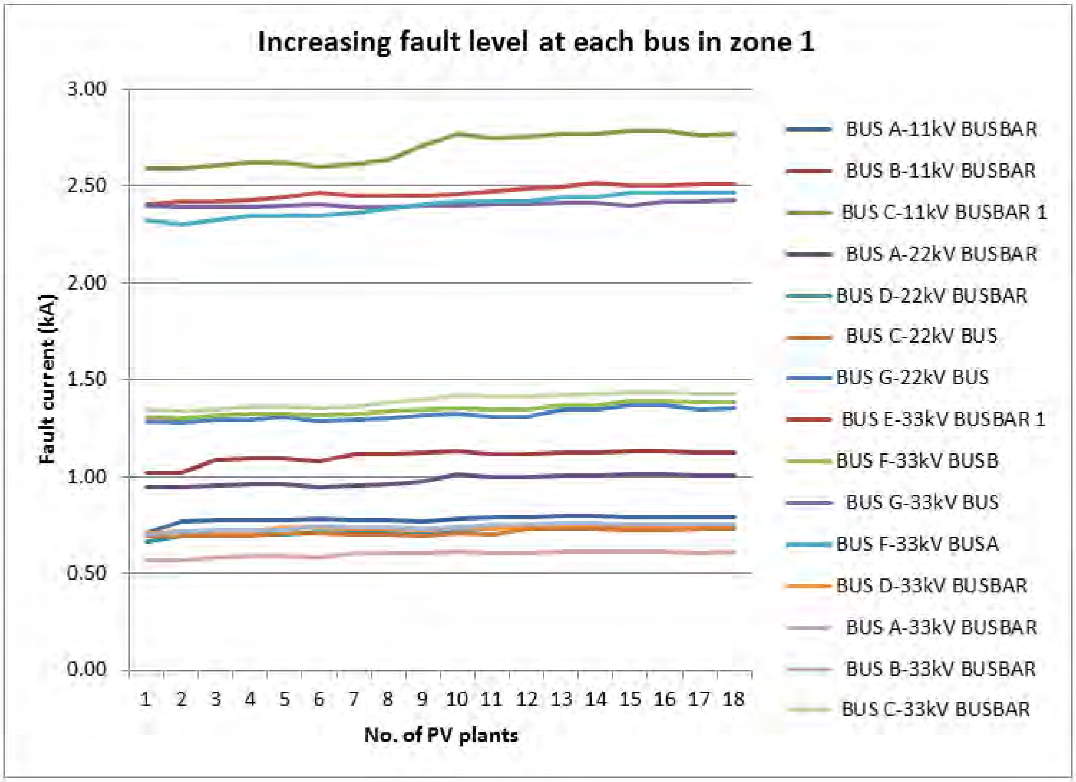


Figure 5-7. Three phase fault level contribution on each busbar with multiple configurations of connecting PV within the Zone 1 area (5MW)

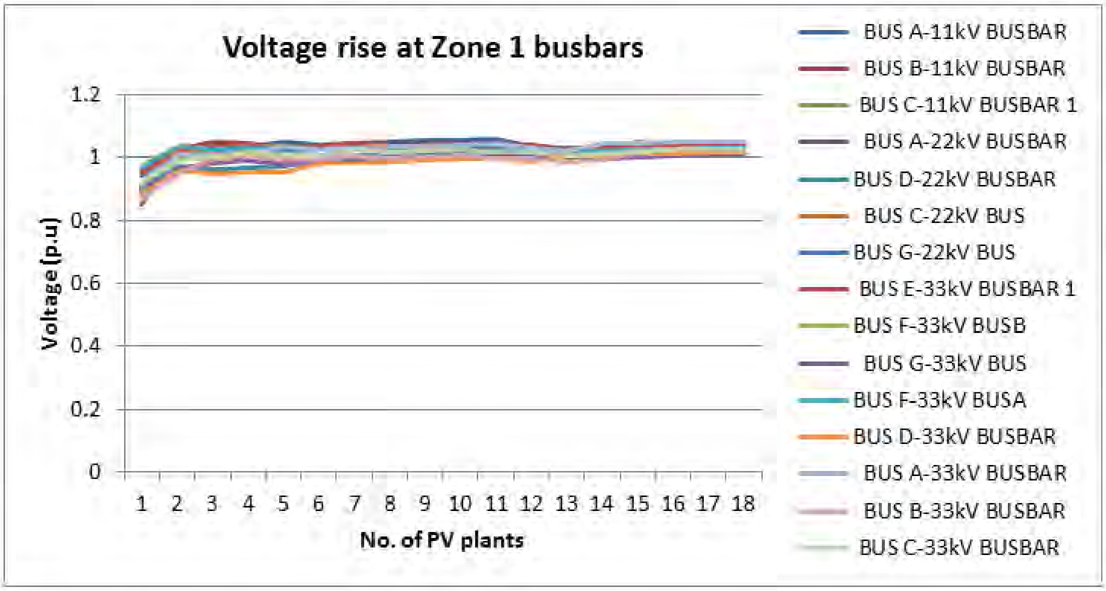


Figure 5-8. P.U voltage rise on relevant busbars, at 2MW 1.06% is reached

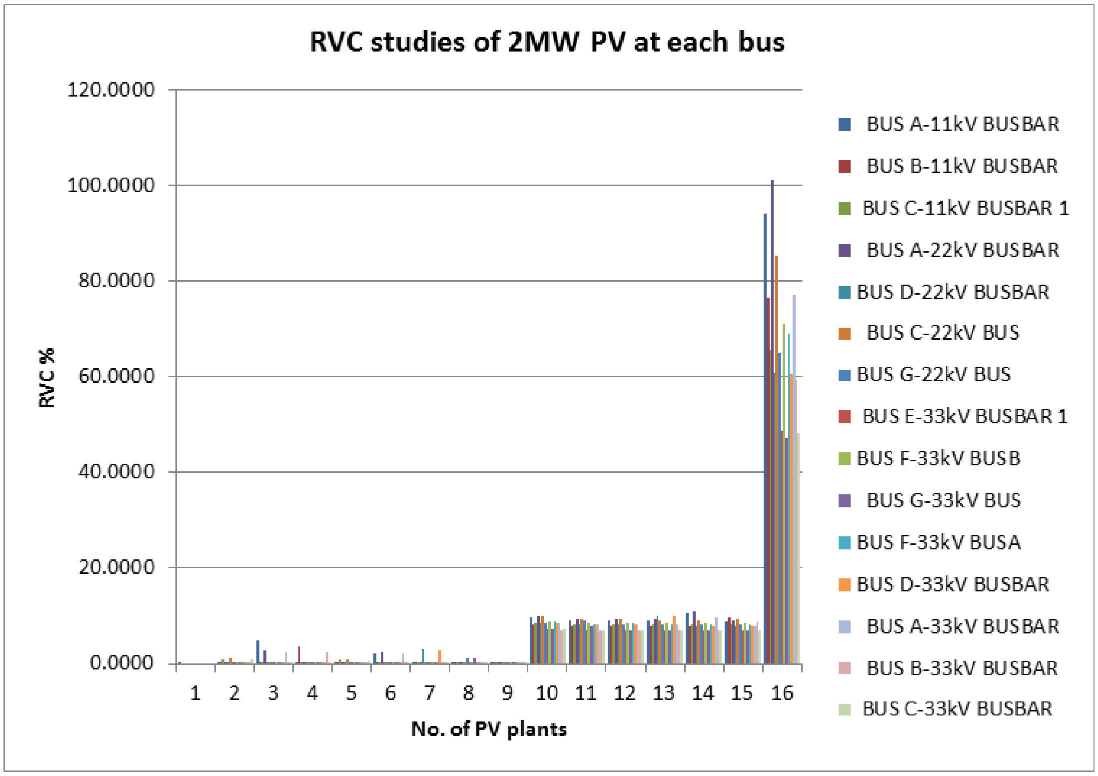


Figure 5-9. Rapid Voltage Change results of connecting PV within the zone 1 area with each 2MW power at off-peak *(RVC>>3%)*

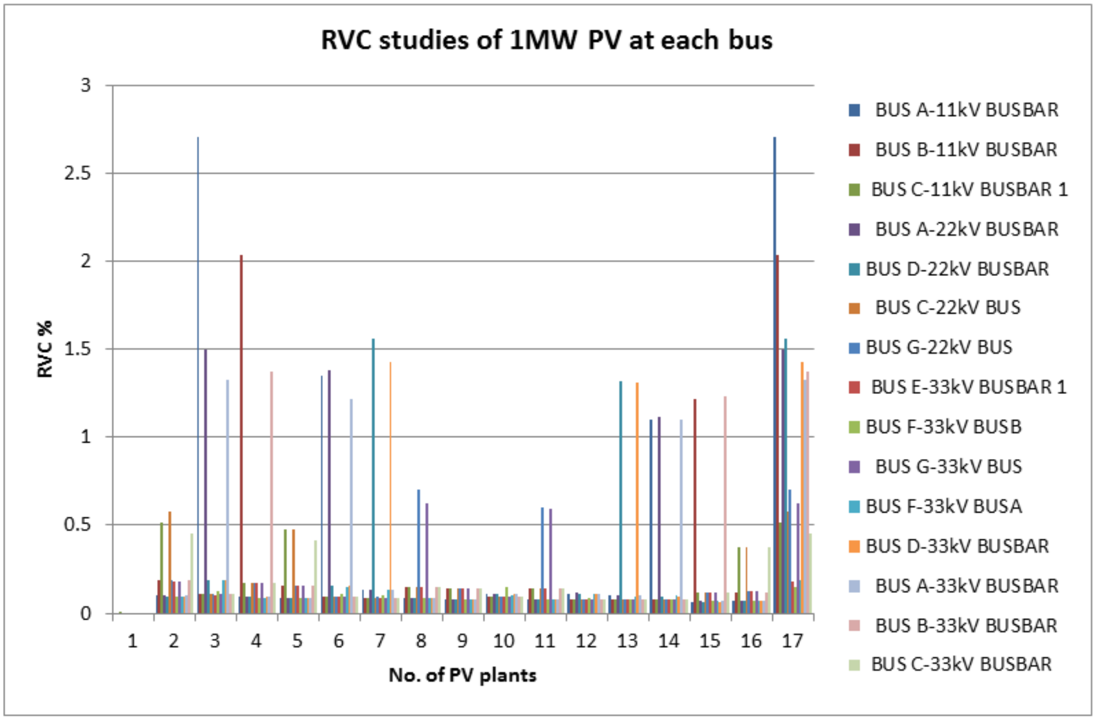


Figure 5-10. Rapid Voltage Change results of connecting PV within the Zone 1 area with each 1MW power at off-peak *(RVC<3%)*

Figure 5-8 shows the voltage rise to 1.06% with connecting PV of 2MW at each busbar. Figure 5-8 shows that this limit is reached prior to RVC studies and 2MW forms the upper bound. RVC studies would therefore have to be carried out at 2MW off-peak. This relatively low value of MW injection indicates the weak network strength and the following is concluded:

1. The p.u steady state voltage rise reaches **1.06%** at **2MW** maximum on each relevant busbar with 31% of substation busbars exceeding RVC values (figure 5-8).
2. During off-peak, **2MW** of generation far exceeds RVC values for all above conditions (figure 5-9) irrespective on the number of buses.
3. During off-peak, **1MW** of connecting power satisfies all test conditions (figure 5-10). This analysis, therefore quantifies, that the maximum PV power that can be connected to any busbar in zone 1 identified above, is **1MW**. The summation of which is, thus, approximately 12MW. This total excludes the 11kV busbars due to practical network configuration and inadequate protection of 22/11kV step-down satellite substations.
4. However, research has shown that 1MW solar farms are not economically practical to install and maintain but larger MW PV farms connecting to higher voltages is more financially feasible. Therefore consideration for analysis is given, only for the two strongest substation busbars, BUS F and BUS E. The maximum power that can be injected into BUS F 132kV busbar is **20MW** and for BUS E 132kV busbar is **22MW**.
5. Total power in zone 1 analysis on existing infrastructure is therefore: **54MW.** This implies that PV installation should be located optimally near these electrical connecting points to extend the benefit of magnitude of PV MW that can be integrated.

A similar analysis is completed for zone 2 and zone 3. Only high voltage connecting points were considered in the studies that follow. Figure 5-11 and 5-12 below, graphically summarizes all the results with the relevant voltage busbars shown in table 5-3 and 5-4. Figure 5-11 show that a power injection at any high voltage busbar in zone 2 may not exceed **12MW** and figure 5-12, **4MW**.

Table 5-3. Affected busbars in the analysis of zone 2

Zone 2
BUS A-132kV-BUSBAR 1 PVZ2
BUS B-132kV BUSBAR PVZ2
BUS C 132kV-BUSBAR 1 PVZ2
BUS D 88kV PVZ2
BUS E=88kV BUS PVZ2
BUS F-132kV T122 PVZ2
BUS G-88kV PVZ2

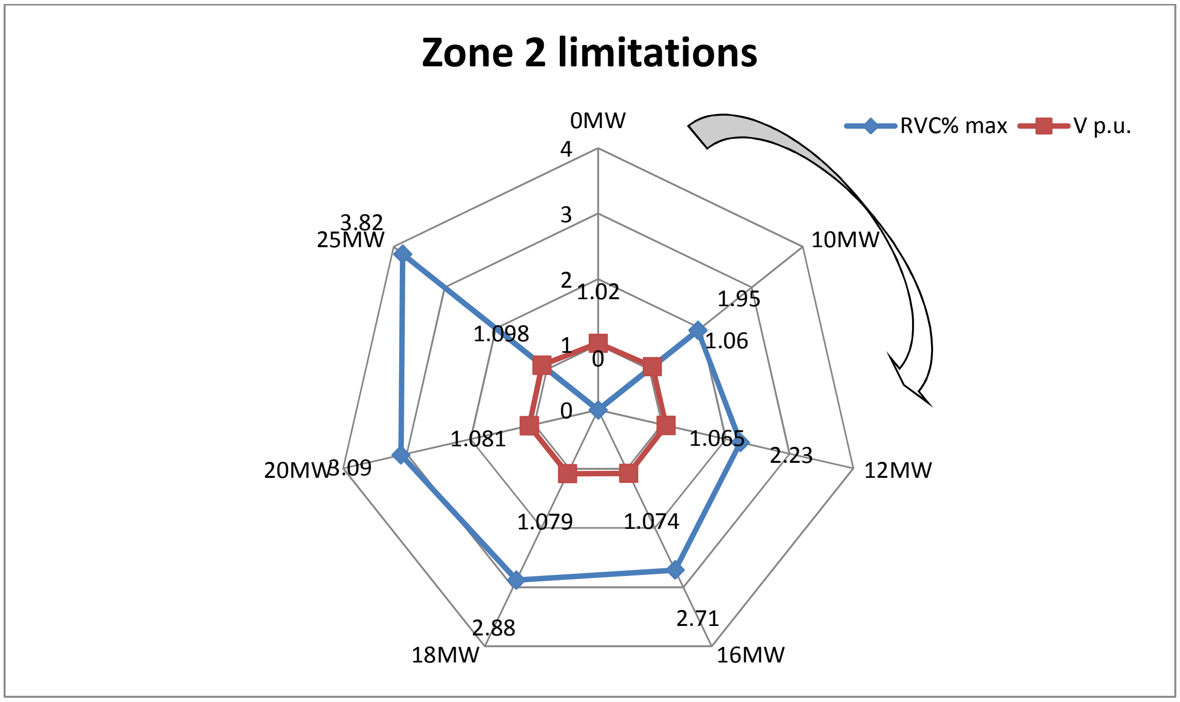


Figure 5-11. Rapid Voltage Change and voltage rise results of connecting PV within zone 2

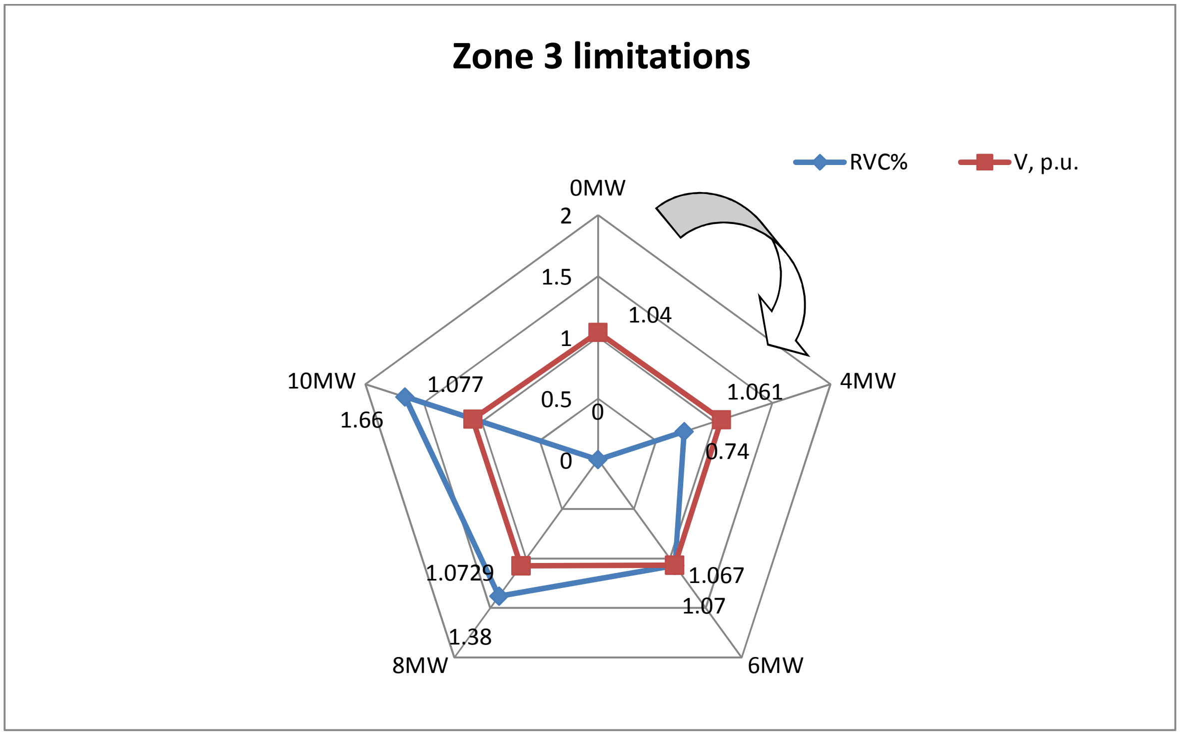


Figure 5-12. Rapid Voltage Change and voltage rise results of connecting PV within zone 3

Table 5-4. Affected busbars in the analysis of zone 3

Zone 3	
BUS A 88KV	BUS G 88KV
BUS B 88KV	BUS H 88KV
BUS C 88KV	BUS I 88KV
BUS D 88KV	BUS J 132KV
BUS E 88KV	BUS K 132KV
BUS F 88KV	

Although figure 5-11 constrains the generating power to 12MW, summating to **72MW** for zone 2, a larger amount of PV power can be connected by eliminating weak high voltage busbars from the analysis. Figure 5-13 shows that if no generation is connected to BUS D, BUS E and BUS G 88kV substations, then at least **50MW** of PV power may be connected to the remaining 132kV substations before any upgrade projects are required. This increases the potential of PV integration to **200MW** for zone 2.

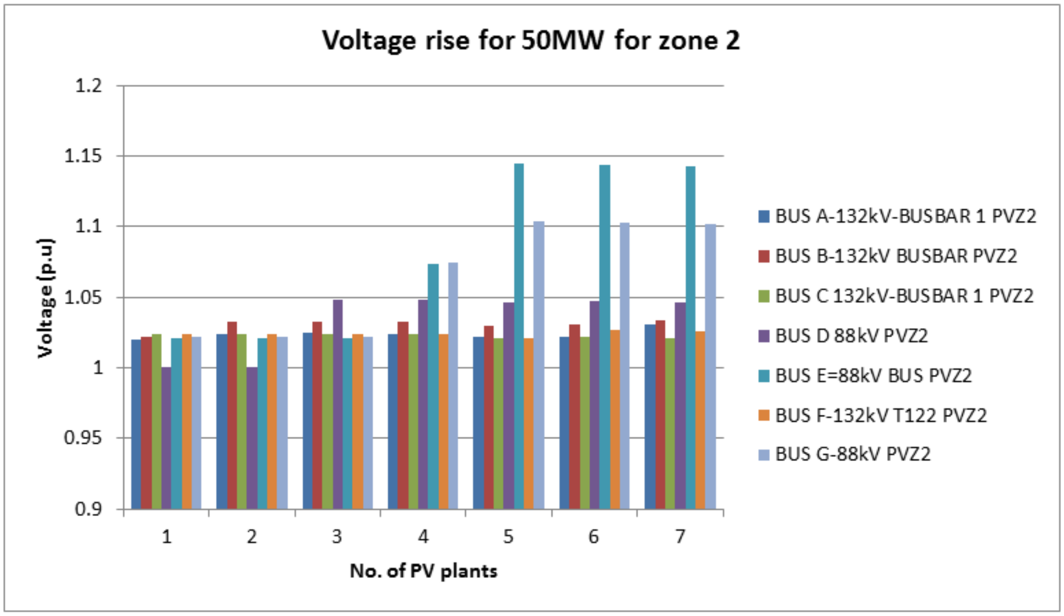


Figure 5-13. Voltage rise results at an RVC of approximately 3% for 50MW

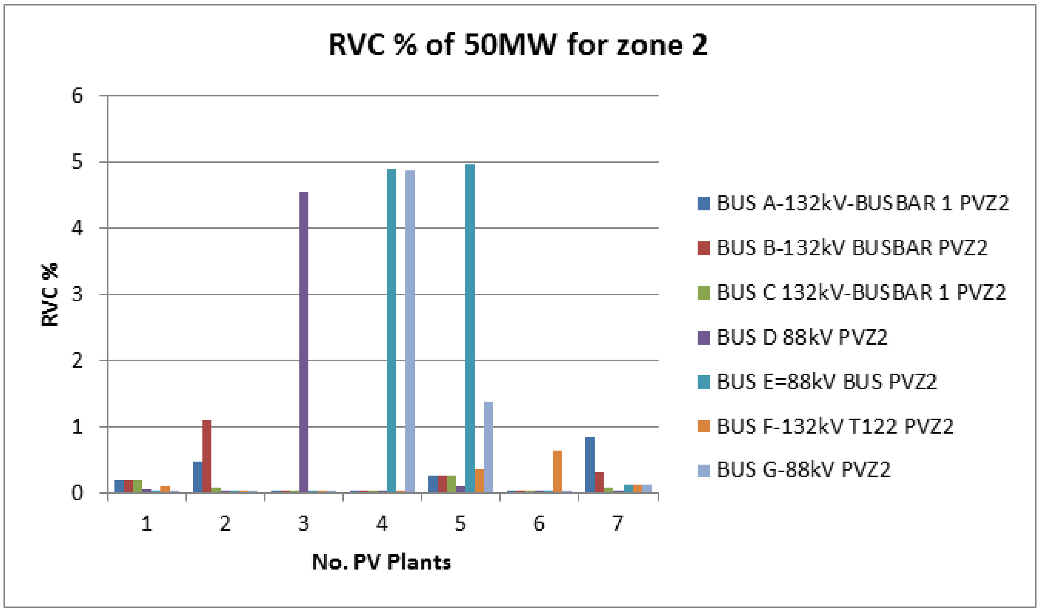


Figure 5-14. RVC studies correlating to voltage rise results of figure 5-13

Similarly, for zone 3, figure 5-15 and 5-16 summarizes the results of the extended analysis. Results show that a maximum of **30MW** of PV power can be connected on BUS B and BUS H 88kV substations without any network upgrade. Results also show that a maximum of **70MW** can be connected on BUS F and BUS I 132kV substations, without any PV on the weak substations as indicated in figure 5-15 and 5-16, and result in values within standard limits. This implies that a maximum of **140MW** of PV power can be connected to the 132kV grid in zone 3.

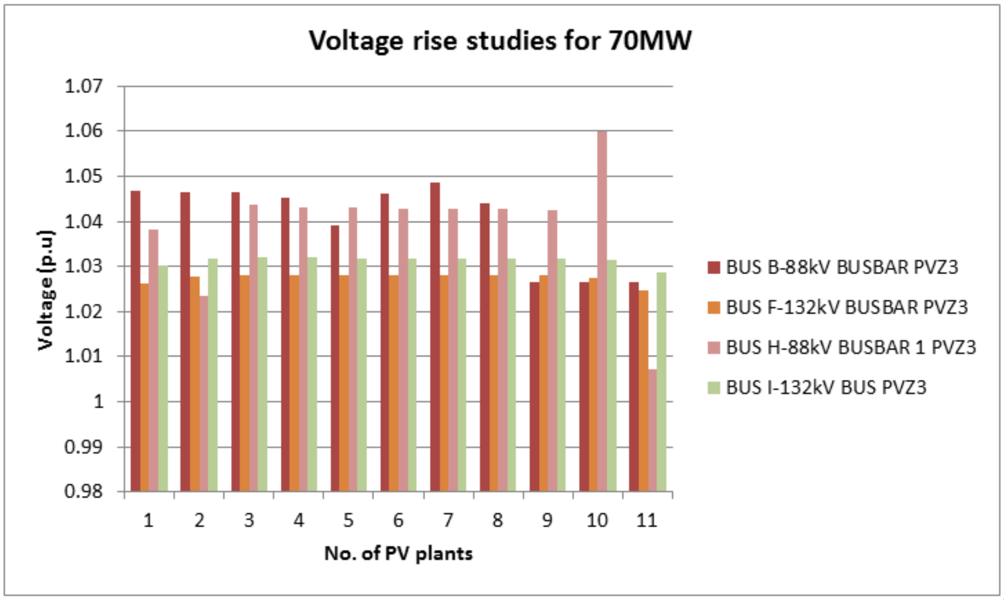


Figure 5-15. Voltage rise results for 70MW

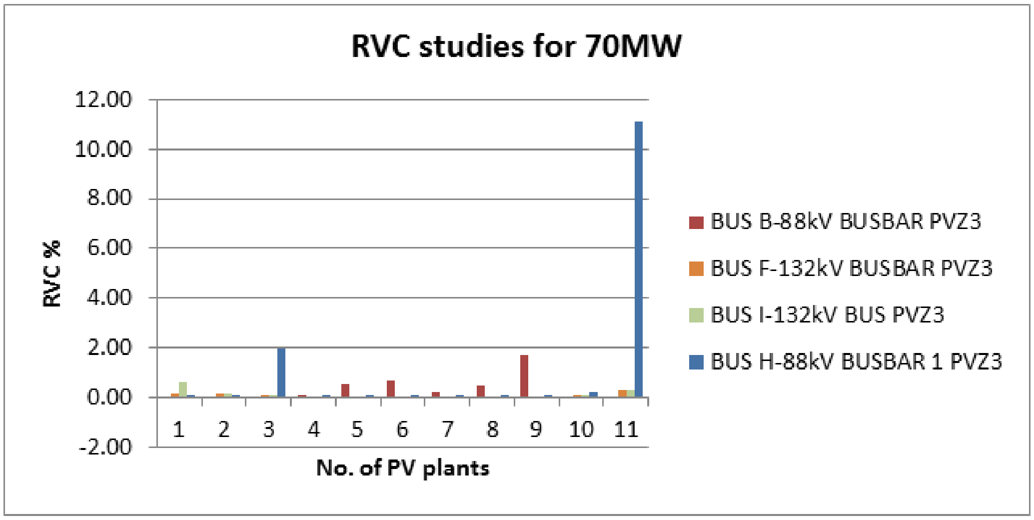


Figure 5-16. RVC studies correlating to voltage rise results of figure 5-15

It can also be seen from figure 5-16 that the RVC value for BUS H exceeds 3% at 70MW. This therefore filters BUS B, BUS F and BUS I. With the practical limitations of substation design for BUS B and interconnecting feeder line capacity to the substation of BUS B, BUS F and BUS I result in the strongest busbars to connect to.

5.3 Summary of case study results

Three viable PV zones have been analysed in the study area for grid integration. The analysis made use of quality supply criteria of RVC, voltage rise and fault level change studies to find suitable MW output levels. All these studies were discussed in chapter 2.

It can therefore be concluded that the maximum MW output on the MV connection side for the zone 1 is 1MW and on the HV side is 20MW. It is also concluded that in terms of the practicality and feasibility of PV projects making them financially justifiable, connections should only be made to the HV system. It is further concluded that the maximum PV MW output that can be connected to zone 2 is 12MW and zone 3 is 4MW (summarized in table 5-5).

The existing limitations in the existing infrastructure on the amount of power to which PV generation can be connected would only be mitigated by establishing transmission injection points. From the viable PV sites in zone 2 and 3, generation power stations in conjunction with the existing converging transmission lines to the station, provide strategic positioning of large PV farms. The MW output derived can only be used to offset off peak load which is still substantial at these zones. The above results are summarized in table 5-5 below:

Table 5-5. Summary of maximum PV power generation that can be connected in each zone

Viable zone	Max connect at each busbar	Specific busbars
Zone 1	1MW	54MW
Zone 2	12MW	200MW
Zone 3	4MW	140MW
Total	**17MW**	**394MW**

An optimal allocation of distributed generation was found in this study. The use of density maps located the most feasible land sites that developers can utilise for their renewable energy projects and also provides more accurate planning to a network development plan. These sites were filtered through by the relevant technical studies and the maximum amount of PV generation that can be connected to existing infrastructure was established. This study can be extended to other forms of renewable energy projects.

6 Conclusions, Recommendations and Future Work

In order to meet the objectives stated in chapter one, three sets of designs were formulated to produce the necessary network planning criteria that would assist a planning engineer and the utility to integrate distributed generation into the network grid. In order to achieve the required result from each design, an electrical model was built and simulated in DIgSILENT Powerfactory. The conclusions of the results derived for each of the dissertation objectives are discussed sections 6.1 to 6.4 below.

6.1 Penetration levels and locating the critical path

From the results found for this design, it can be concluded that the combined effects of multiple generator units plays a significant role on the fault level at any generator connecting point sharing the same infrastructure. Practically, all equipment is rated at a short circuit current carrying value and can therefore be compromised in the existing system. The DPL script that was designed for and executed on the test grid, located the critical path of components that were affected by the combined fault level of the existing system and the short circuit currents contributions of all connected generators sharing the same infrastructure or connected in close proximity to one another.

In order to assess the effect on the network with the proposed connected generators, the planning engineer will execute the script by first filtering the machines that require analysis. At the end of the script execution, a set of components will be filtered out and can be identified as building blocks that make up one or several critical paths. The script has the following advantages:

- ✓ Results may indicate that distributed generation at alternative connection points, to that initially used, could be more suitable from a technical and financial effectiveness perspective.
- ✓ Weak points in the existing networks may also be identified and may assist the utility in prioritising capital strengthening projects.
- ✓ It is also found that in light loaded conditions, with generators at full operation, line and transformer loadings increase more than during peak conditions, where there is not enough localised load to absorb the injected power.
- ✓ On large interconnected networks, iron, copper, aluminium and steel electrical losses may prove to be very costly. The tool may therefore suggest favourable injection points minimizing these losses.

It can be concluded that the DPL script provides the utility with an improved network planning approach as weak network components are identified not only for forward power flow but reverse power flow as well. This analysis may then be documented in the utility's network development plans. A developer and the utility may both contribute to a strengthening project that was not of investment grade status when funded in isolation. This approach will also will accelerate capital projects that were previously financially constrained.

With the release of the updated version of DIgSILENT Powerfactory, the DPL scripting performing the above analysis may be assigned to a control and its use will be even more practical. An extended analysis may be undertaken using the DPL script to calculate generator reliability. With different loading conditions and generator operation times, the most optimal timeline may be derived from the script analysis, to have each generator operate within a specified load period.

The advantage of such a tool enables cost effective infrastructure planning, utility capital project prioritization and the creation of entry points to improve network performance.

6.2 Voltage stability

When the integration of a generator to the grid successfully surpasses all steady state studies and adheres to all grid codes, its dynamic performance after a system disturbance was then analysed. The analysis was more complex in the multi-machine scenario. The model used in design two analyses used two sources to control the network strength. In reality, the model represents a sub-set of any HV network. During peak load, and maximum generation, a disturbance was created by the sudden disconnection of one of the three generators in the model. Data points that described the voltage stability curves at the relevant busbars were recorded and exported to excel for data analysis. It was found that by using standard deviation and voltage regulation limits, the ratio of network strength values to generator short circuit current values produced the following results, which is again tabulated in table 6.1.

Table 6-1. Summary of results for grid to machine ratios

Grid strength	3% Volt drop	5% Volt drop
1-5kA	2.9	1.71
4-10kA	3.6	2.06
10-15kA	3.7	2.12

In each network strength range, if the utility was to connect a generator to a grid that had a fault current rating of 5kA, to prevent a 3% drop in voltage in that network range, a generator that has a short circuit current rating value of (5/3.6) can be connected to this grid i.e. no more than 1.38kA rating. With generators rated lower than this value, voltage busbars in close proximity do not experience any instability as long as the above ratio is maintained.

It is concluded that table 6-1 can be used as a rule of thumb where voltage stability in a multi-machine scenario becomes a deciding factor to a successful integration. This implies that further network upgrades can be prevented or even amended to cater for this need. This would therefore enable cost effective infrastructure planning.

6.3 Network configurations

The configuration types formulised in chapter four (figure 4-19 to 4-22) may be used by the planning engineer and utility to practically integrate DG to grid infrastructure. As discussed, the four types identified depend on generation magnitude and connecting voltage. As tabulated in table 6-2 for completion, a summary of the different types and connecting voltage is shown.

Table 6-2. Summary of results of configuration types

Connecting Voltage	Type 1	Type 2	Type 3	Type 4
11kV	< 2.5MVA	< 13MVA	N/A	N/A
22kV	< 5MVA	< 27MVA	N/A	N/A
33kV	N/A	N/A	< 28MVA	< 28MVA
33kV> & <88kV	N/A	N/A	< 56MVA	< 56MVA
88kV	N/A	N/A	< 75MVA	< 75MVA
132kV	N/A	N/A	< 112MVA	< 112MVA

In addition to figure 6-2, a planning engineer or developer may use all the cost estimates in chapter four in calculating an engineering cost estimate of integrating DG to the proposed electrical infrastructure. It is concluded that the engineering connection process established in chapter 4.3 can easily be adopted in its use.

6.4 Study case: Optimal allocation of PV

The analysis used in this study case made use of the technical studies discussed in chapter two, i.e. quality supply criteria of RVC, voltage rise and fault level change studies. It is concluded that in all three zones, not all existing infrastructure was capable of connecting DG. In fact the magnitude of connected generation is low unless only the strongest substations are used for the integration. The results derived for all three zones correlate to this conclusion. A summary of the maximum generation of all busbars per zone as well as on the strongest substation busbars are tabulated for completion in table 6-3 below.

Table 6-3. Summary of results of study case

Viable zone	**Max connect at each busbar**	**Specific busbars**
Zone 1	1MW	54MW
Zone 2	12MW	200MW
Zone 3	4MW	140MW
Total	**17MW**	**394MW**

6.5 Recommendations

In order to integrate distributed generation to the utility grid the planner should ensure that all data gathered is accurate and practical. Equipment type specifications, network information and times of operation are key factors that need to be taken into account. Planning criteria are a first pass study for distributed generation integration. It is recommended that especially for co-generation plants, internal machines such as large motors etc. be accounted for. All synchronous motors contribute to the increase in the three phase short circuit current at the connecting busbar.

6.6 Future work

The study case results may be extended to other technology forms such as wind and biomass. These data files can be sourced, integrated with the utility's electrical network and a similar analysis performed as per chapter five. An optimal allocation of all the different technologies can be found which will truly be invaluable to developers and the utility in future planning.

Future network development plans should use all the planning criteria derived in this dissertation to analyse possible renewable generation plants in that planning study area. A renewable energy forecast can then be derived and merged with the study area existing load forecast.

Grid to generator ratios can be calculated for other different technologies. The proposed results would provide more accuracy to the results established in Table 6-1.

Aggregated network development plans should be integrated into the South African energy resource plans to ensure efficient economic rollout of various energy tariffs together with its allocation to each category of energy technology, for maximum sustainable beneficiation.

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APPENDIX A1

Grid 1: 1kA **Grid 2: 1kA** Machine: 1	**Bus 4**	**Bus 3**	**Bus 2**	**Bus 1**
Time in s	**Magnitude in p.u.**			
-0.1	1	1	0.9995	0.9996
-0.09	1	1	0.9995	0.9996
-0.08	1	1	0.9995	0.9996
-0.07	1	1	0.9995	0.9996
-0.06	1	1	0.9995	0.9996
-0.05	1	1	0.9995	0.9996
-0.04	1	1	0.9995	0.9996
-0.03	1	1	0.9995	0.9996
-0.02	1	1	0.9995	0.9996
-0.01	1	1	0.9995	0.9996
0	1	1	0.9995	0.9996
0.01	1	1	0.9995	0.9996
0.025	1	1	0.9995	0.9996
0.04	1	1	0.9995	0.9996
0.055	1	1	0.9995	0.9996
0.07	1	1	0.9995	0.9996
0.085	1	1	0.9995	0.9996
0.1	1	1	0.9995	0.9996
0.115	1	1	0.9995	0.9996
0.13	1	1	0.9995	0.9996
0.145	1	1	0.9995	0.9996
0.16	1	1	0.9995	0.9996
0.175	1	1	0.9995	0.9996
0.1975	1	1	0.9995	0.9996
0.2	1	1	0.9995	0.9996
0.205	0.9953	0.9954	0.9949	0.9949
0.2118	0.9953	0.9953	0.9948	0.9949
0.2218	0.9952	0.9952	0.9947	0.9948
0.2318	0.9951	0.9951	0.9946	0.9947
0.2418	0.995	0.995	0.9945	0.9946
0.2518	0.9949	0.9949	0.9944	0.9945
0.2618	0.9949	0.9949	0.9944	0.9945
0.2718	0.9949	0.9949	0.9944	0.9945
0.2818	0.9949	0.9949	0.9944	0.9945
0.2918	0.9949	0.995	0.9945	0.9945
0.3	0.995	0.995	0.9945	0.9946
0.305	0.9446	0.9448	0.9441	0.9439

0.3118	0.9433	0.9435	0.9428	0.9426
0.3218	0.949	0.9492	0.9485	0.9483
0.3318	0.9647	0.9648	0.9642	0.9641
0.3418	0.9858	0.9858	0.9853	0.9853
0.3518	0.9983	0.9983	0.9978	0.9979
0.3618	0.9954	0.9954	0.9949	0.995
0.3718	0.9836	0.9836	0.9831	0.9831
0.3818	0.9716	0.9717	0.9711	0.9711
0.3918	0.9641	0.9642	0.9636	0.9635
0.4018	0.9636	0.9638	0.9631	0.9631
0.4118	0.9706	0.9708	0.9702	0.9701
0.4218	0.9822	0.9823	0.9818	0.9818
0.4318	0.9932	0.9932	0.9927	0.9928
0.4418	0.9999	0.9999	0.9994	0.9995
0.4518	1.0022	1.0022	1.0017	1.0018
0.4618	1.0022	1.0021	1.0017	1.0018
0.4718	1.0018	1.0018	1.0013	1.0015
0.4818	1.0024	1.0024	1.0019	1.002
0.4918	1.0038	1.0037	1.0033	1.0034
0.5	1.0044	1.0044	1.0039	1.0041
0.505	1.0044	1.0044	1.0039	1.0041
0.5118	1.0035	1.0034	1.003	1.0031
0.5218	1.0004	1.0004	1	1
0.5368	0.9947	0.9947	0.9942	0.9943
0.5518	0.9909	0.991	0.9904	0.9905
0.5668	0.991	0.991	0.9905	0.9906
0.5818	0.9939	0.9939	0.9934	0.9935
0.5968	0.9976	0.9976	0.9971	0.9972
0.6118	1.0006	1.0006	1.0001	1.0002
0.6268	1.0026	1.0026	1.0021	1.0022
0.6418	1.0036	1.0036	1.0031	1.0033
0.6568	1.0035	1.0035	1.003	1.0032
0.6718	1.0023	1.0023	1.0018	1.0019
0.6868	1.0003	1.0003	0.9998	0.9999
0.7018	0.9984	0.9984	0.9979	0.998
0.7168	0.9973	0.9973	0.9968	0.9969
0.7318	0.9972	0.9972	0.9967	0.9968
0.7468	0.9979	0.9979	0.9974	0.9975
0.7618	0.9991	0.9992	0.9987	0.9988
0.7768	1.0004	1.0004	0.9999	1
0.7918	1.0014	1.0014	1.0009	1.001
0.8	1.0016	1.0016	1.0011	1.0012
0.805	1.0016	1.0016	1.0012	1.0013
0.8118	1.0017	1.0016	1.0012	1.0013

0.8218	1.0015	1.0015	1.001	1.0011
0.8318	1.0012	1.0012	1.0007	1.0008
0.8418	1.0007	1.0007	1.0002	1.0003
0.8518	1.0002	1.0002	0.9997	0.9999
0.8618	0.9998	0.9998	0.9993	0.9994
0.8718	0.9994	0.9994	0.9989	0.999
0.8818	0.9992	0.9992	0.9987	0.9988
0.8968	0.9992	0.9992	0.9987	0.9988
0.9118	0.9994	0.9994	0.9989	0.999
0.9268	0.9998	0.9998	0.9994	0.9995
0.9418	1.0003	1.0003	0.9998	0.9999
0.9568	1.0006	1.0006	1.0001	1.0002
0.9718	1.0008	1.0008	1.0003	1.0004
0.9868	1.0007	1.0007	1.0002	1.0003
1	1.0005	1.0005	1	1.0001
1.005	1.0004	1.0004	0.9999	1
1.0118	1.0003	1.0003	0.9998	0.9999
1.0218	1.0001	1.0001	0.9996	0.9997
1.0368	0.9999	0.9999	0.9994	0.9995
1.0518	0.9998	0.9998	0.9993	0.9994
1.0668	0.9998	0.9998	0.9993	0.9995
1.0818	1	1	0.9995	0.9996
1.0968	1.0001	1.0001	0.9996	0.9997
1.1118	1.0003	1.0003	0.9998	0.9999
1.1268	1.0004	1.0004	0.9999	1
1.1418	1.0004	1.0004	0.9999	1
1.1568	1.0004	1.0004	0.9999	1
1.1718	1.0003	1.0003	0.9998	0.9999
1.1868	1.0002	1.0002	0.9997	0.9998
1.2093	1.0001	1.0001	0.9996	0.9997
1.2318	1.0001	1.0001	0.9996	0.9997
1.2543	1.0001	1.0001	0.9997	0.9998
1.2768	1.0002	1.0002	0.9997	0.9998
1.2993	1.0003	1.0003	0.9998	0.9999
1.3218	1.0003	1.0003	0.9998	0.9999
1.3443	1.0002	1.0002	0.9997	0.9998
1.3668	1.0002	1.0002	0.9997	0.9998
1.3893	1.0001	1.0001	0.9997	0.9998
1.4118	1.0002	1.0002	0.9997	0.9998
1.4343	1.0002	1.0002	0.9997	0.9998
1.468	1.0002	1.0002	0.9997	0.9998
1.5018	1.0002	1.0002	0.9997	0.9998
1.5355	1.0002	1.0002	0.9997	0.9998
1.5693	1.0002	1.0002	0.9997	0.9998

1.603	1.0002	1.0002	0.9997	0.9998
1.6368	1.0002	1.0002	0.9997	0.9998
1.6705	1.0002	1.0002	0.9997	0.9998
1.7043	1.0002	1.0002	0.9997	0.9998
1.738	1.0002	1.0002	0.9997	0.9998
1.7718	1.0001	1.0001	0.9997	0.9998
1.8055	1.0002	1.0002	0.9997	0.9998
1.8055	1.0002	1.0002	0.9997	0.9998
1.8308	0.9984	0.9984	0.9979	0.998
1.8308	0.9984	0.9984	0.9979	0.998
1.8435	0.9998	0.9998	0.9993	0.9995
1.8561	0.9993	0.9993	0.9988	0.9989
1.8688	0.998	0.998	0.9975	0.9976
1.8814	0.9974	0.9974	0.9969	0.9971
1.8941	0.9978	0.9979	0.9974	0.9975
1.9068	0.9987	0.9987	0.9982	0.9983
1.9194	0.9993	0.9993	0.9988	0.9989
1.9321	0.9997	0.9997	0.9992	0.9993
1.9447	0.9999	0.9999	0.9994	0.9995
1.9574	1.0004	1.0004	0.9999	1
1.97	1.0009	1.0008	1.0004	1.0005
1.9827	1.0011	1.0011	1.0006	1.0007
1.9954	1.001	1.001	1.0005	1.0006
2.008	1.0005	1.0005	1	1.0001
2.0207	0.9999	0.9999	0.9994	0.9996
2.0333	0.9995	0.9995	0.999	0.9991
2.046	0.9993	0.9993	0.9988	0.9989
2.0586	0.9993	0.9993	0.9988	0.9989
2.0713	0.9995	0.9995	0.999	0.9991
2.0839	0.9997	0.9997	0.9992	0.9993
2.0966	0.9999	0.9999	0.9994	0.9995
2.1093	1.0002	1.0002	0.9997	0.9998
2.1219	1.0005	1.0004	1	1.0001
2.1346	1.0006	1.0006	1.0001	1.0002
2.1472	1.0006	1.0006	1.0001	1.0002
2.1599	1.0005	1.0005	1	1.0001
2.1789	1.0002	1.0002	0.9997	0.9998
2.1979	1	1	0.9995	0.9996
2.2168	0.9999	0.9999	0.9994	0.9995
2.2358	0.9999	0.9999	0.9994	0.9995
2.2548	1	1	0.9995	0.9996
2.2738	1.0002	1.0002	0.9997	0.9998
2.2928	1.0003	1.0003	0.9998	0.9999
2.3118	1.0004	1.0004	0.9999	1

2.3307	1.0003	1.0003	0.9998	0.9999
2.3497	1.0002	1.0002	0.9997	0.9998
2.3687	1.0001	1.0001	0.9996	0.9997
2.3877	1.0001	1.0001	0.9996	0.9997
2.4162	1.0001	1.0001	0.9996	0.9997
2.4447	1.0002	1.0002	0.9997	0.9998
2.4731	1.0003	1.0003	0.9998	0.9999
2.5016	1.0003	1.0003	0.9998	0.9999
2.5301	1.0002	1.0002	0.9997	0.9998
2.5586	1.0002	1.0002	0.9997	0.9998
2.587	1.0002	1.0002	0.9997	0.9998
2.6155	1.0002	1.0002	0.9997	0.9998
2.644	1.0003	1.0003	0.9998	0.9999
2.6725	1.0003	1.0003	0.9998	0.9999
2.7009	1.0002	1.0002	0.9998	0.9999
2.7009	1.0002	1.0002	0.9998	0.9999
2.7223	1.0002	1.0002	0.9997	0.9998
2.7437	1.0002	1.0002	0.9997	0.9998
2.765	1.0002	1.0002	0.9997	0.9998
2.7864	1.0002	1.0002	0.9998	0.9999
2.8077	1.0003	1.0003	0.9998	0.9999
2.8291	1.0003	1.0003	0.9998	0.9999
2.8504	1.0003	1.0003	0.9998	0.9999
2.8718	1.0002	1.0002	0.9998	0.9999
2.8932	1.0002	1.0002	0.9997	0.9999
2.9145	1.0002	1.0002	0.9997	0.9998
2.9359	1.0002	1.0002	0.9997	0.9998
2.9679	1.0002	1.0002	0.9997	0.9999
2.9999	1.0002	1.0002	0.9997	0.9999

APPENDIX A2

Grid 1: 3 **Grid 2: 4** Machine: 21	**Bus 4**	**Bus 3**	**Bus 2**	**Bus 1**
Time in s	**Magnitude in p.u.**			
-0.1	1	1	1.0002	1.0003
-0.09	1	1	1.0002	1.0003
-0.08	1	1	1.0002	1.0003
-0.07	1	1	1.0002	1.0003
-0.06	1	1	1.0002	1.0003
-0.05	1	1	1.0002	1.0003
-0.04	1	1	1.0002	1.0003
-0.03	1	1	1.0002	1.0003
-0.02	1	1	1.0002	1.0003
-0.01	1	1	1.0002	1.0003
0	1	1	1.0002	1.0003
0.01	1	1	1.0002	1.0003
0.025	1	1	1.0002	1.0003
0.04	1	1	1.0002	1.0003
0.055	1	1	1.0002	1.0003
0.07	1	1	1.0002	1.0003
0.085	1	1	1.0002	1.0003
0.1	1	1	1.0002	1.0003
0.115	1	1	1.0002	1.0003
0.13	1	1	1.0002	1.0003
0.145	1	1	1.0002	1.0003
0.16	1	1	1.0002	1.0003
0.175	0.9981	0.9982	0.9982	0.998
0.1975	0.9982	0.9982	0.9982	0.998
0.2	0.9983	0.9984	0.9984	0.9982
0.205	0.9987	0.9988	0.9987	0.9985
0.2118	0.9991	0.9992	0.9991	0.999
0.2218	0.9995	0.9996	0.9996	0.9994
0.2318	0.9999	1.0001	1	0.9998
0.2418	1.0003	1.0004	1.0003	1.0002
0.2518	1.0006	1.0007	1.0006	1.0005
0.2618	1.0009	1.001	1.0009	1.0007
0.2718	1.001	1.0011	1.001	1.0009
0.2818	0.7639	0.7655	0.7638	0.7601
0.2918	0.7444	0.7462	0.7442	0.7399
0.3	0.7233	0.7252	0.7229	0.7179
0.305	0.7083	0.7103	0.7079	0.7023

0.3118	0.6956	0.6977	0.6952	0.6893
0.3218	0.6834	0.6855	0.683	0.6768
0.3318	0.6707	0.6729	0.6704	0.6641
0.3418	0.6577	0.6599	0.6575	0.651
0.3518	0.6447	0.6469	0.6445	0.6379
0.3618	0.6323	0.6345	0.632	0.6253
0.3718	0.6214	0.6238	0.6211	0.6141
0.3818	0.6136	0.6161	0.6132	0.606
0.3918	0.6124	0.6151	0.6118	0.6043
0.4018	0.6264	0.6292	0.6255	0.6179
0.4118	0.6731	0.6758	0.672	0.6651
0.4218	0.7716	0.7736	0.7706	0.7655
0.4318	0.8955	0.8965	0.895	0.8923
0.4418	0.985	0.9853	0.985	0.9844
0.4518	1.0057	1.0058	1.0059	1.0065
0.4618	0.9648	0.9652	0.9651	0.9656
0.4718	0.9019	0.9028	0.902	0.9016
0.4818	0.8648	0.8659	0.8648	0.8638
0.4918	0.8115	0.813	0.8113	0.8091
0.5	0.74	0.7422	0.7394	0.7352
0.505	0.6931	0.6957	0.6921	0.6859
0.5118	0.6739	0.6768	0.6726	0.6651
0.5218	0.692	0.6948	0.6906	0.6828
0.5318	0.7692	0.7713	0.7679	0.7616
0.5418	0.8904	0.8915	0.8896	0.8862
0.5518	0.9867	0.987	0.9866	0.9857
0.5618	1.0127	1.0127	1.0131	1.0135
0.5718	0.9667	0.9668	0.9675	0.9678
0.5818	0.8711	0.8717	0.8719	0.8708
0.5918	0.7546	0.756	0.7551	0.7516
0.6018	0.6574	0.6599	0.6572	0.6506
0.6118	0.6353	0.6384	0.6344	0.6262
0.6218	0.7321	0.7346	0.7311	0.7247
0.6318	0.8889	0.89	0.8885	0.8858
0.6418	0.9853	0.9856	0.9857	0.9855
0.6518	0.9785	0.9785	0.9794	0.9799
0.6618	0.8842	0.8847	0.8852	0.8845
0.6718	0.7426	0.7444	0.743	0.7393
0.6818	0.6411	0.6442	0.6404	0.6326
0.6918	0.7102	0.7129	0.7089	0.7015
0.7018	0.8958	0.8969	0.8951	0.8919
0.7118	1.0076	1.0079	1.0077	1.0076
0.7218	0.9918	0.992	0.9922	0.9929
0.7318	0.8726	0.8737	0.8731	0.8721

0.7418	0.7084	0.7109	0.7081	0.703
0.7518	0.6538	0.657	0.6524	0.6439
0.7618	0.8179	0.8196	0.8168	0.8116
0.7718	0.9541	0.9547	0.9537	0.9519
0.7818	1.0101	1.0103	1.0101	1.0099
0.7918	1.0146	1.0148	1.0151	1.0157
0.8	0.9178	0.9185	0.9186	0.9183
0.805	0.7418	0.7438	0.7421	0.738
0.8118	0.6354	0.6388	0.6345	0.6259
0.8218	0.7843	0.7864	0.7833	0.7776
0.8318	0.9678	0.9684	0.9678	0.9666
0.8418	1.002	1.0022	1.0029	1.0035
0.8518	0.8842	0.8848	0.8853	0.8846
0.8618	0.6813	0.6836	0.6816	0.6761
0.8718	0.6508	0.654	0.6496	0.6411
0.8818	0.8816	0.8829	0.881	0.8777
0.8918	1.0075	1.0077	1.008	1.0082
0.9018	0.9416	0.942	0.9426	0.9428
0.9118	0.7336	0.7356	0.7341	0.7301
0.9218	0.6386	0.6419	0.6373	0.6285
0.9318	0.8788	0.8801	0.8781	0.8745
0.9418	1.0174	1.0176	1.0177	1.018
0.9518	0.9399	0.9405	0.9407	0.9409
0.9618	0.7095	0.7119	0.7095	0.7046
0.9718	0.6749	0.678	0.6736	0.6655
0.9818	0.7748	0.7769	0.7735	0.7674
0.9918	0.9516	0.9522	0.9511	0.9492
1	1.0171	1.0172	1.0176	1.0184
1.005	0.849	0.8502	0.8496	0.8483
1.0118	0.6271	0.6306	0.6261	0.6175
1.0218	0.8418	0.8433	0.8408	0.8362
1.0318	1.0211	1.0213	1.0214	1.0216
1.0418	0.9327	0.9332	0.9336	0.9336
1.0518	0.663	0.6658	0.6628	0.6564
1.0618	0.7535	0.7558	0.7523	0.7457
1.0718	1	1.0003	1.0001	0.9997
1.0818	0.9606	0.9609	0.9616	0.9621
1.0918	0.6846	0.687	0.6849	0.6795
1.1018	0.7241	0.7267	0.7228	0.7158
1.1118	0.9942	0.9945	0.9943	0.9938
1.1218	0.9531	0.9534	0.9542	0.9546
1.1318	0.6598	0.6624	0.6599	0.6538
1.1418	0.769	0.7712	0.7678	0.7618
1.1518	1.0135	1.0137	1.0138	1.0139

1.1618	0.9081	0.9086	0.9091	0.9089
1.1718	0.6139	0.6173	0.613	0.6046
1.1818	0.8776	0.8788	0.8768	0.8731
1.1918	1.0217	1.0218	1.0223	1.0231
1.2018	0.7975	0.7989	0.7981	0.7958
1.2118	0.6642	0.6673	0.6627	0.6541
1.2218	0.9905	0.9908	0.9903	0.9894
1.2318	0.9619	0.9622	0.9627	0.9633
1.2418	0.6356	0.6387	0.635	0.6276
1.2518	0.8594	0.8607	0.8584	0.8543
1.2618	1.0262	1.0261	1.0266	1.0275
1.2718	0.7797	0.7811	0.7801	0.7775
1.2818	0.6994	0.7021	0.6978	0.69
1.2918	1.0142	1.0144	1.0143	1.0142
1.3018	0.9012	0.9016	0.902	0.9018
1.3118	0.6104	0.6138	0.609	0.5997
1.3218	0.9614	0.9619	0.961	0.9595
1.3318	0.9686	0.9686	0.9694	0.9702
1.3418	0.6152	0.6183	0.6145	0.6066
1.3518	0.9016	0.9026	0.9009	0.8979
1.3618	1.0004	1.0003	1.0012	1.0022
1.3718	0.6514	0.6539	0.6511	0.6449
1.3818	0.8588	0.8602	0.8579	0.8539
1.3918	1.014	1.0138	1.0147	1.0157
1.4018	0.6753	0.6775	0.6752	0.6699
1.4118	0.844	0.8454	0.843	0.8386
1.4218	1.0183	1.018	1.0188	1.0199
1.4318	0.6743	0.6765	0.6741	0.6687
1.4418	0.8574	0.8588	0.8565	0.8523
1.4518	1.0146	1.0144	1.0152	1.0163
1.4618	0.6493	0.6518	0.6488	0.6424
1.4718	0.8945	0.8956	0.8937	0.8904
1.4818	0.9982	0.998	0.9988	0.9999
1.4918	0.6133	0.6163	0.6123	0.6042
1.5018	0.947	0.9476	0.9464	0.9444
1.5118	0.9583	0.9582	0.9589	0.9597
1.5218	0.6044	0.6078	0.6029	0.5935
1.5318	1.0008	1.0009	1.0007	1.0001
1.5418	0.8766	0.8769	0.8772	0.8768
1.5518	0.6807	0.6835	0.6791	0.6709
1.5618	1.0321	1.0318	1.0323	1.0331
1.5718	0.7371	0.7384	0.7373	0.7339
1.5818	0.8344	0.8359	0.8333	0.8286
1.5918	1.0074	1.0071	1.0081	1.0093

1.6018	0.6003	0.6034	0.5992	0.5907
1.6118	0.9783	0.9786	0.978	0.9769
1.6218	0.8891	0.8892	0.8898	0.8896
1.6318	0.6901	0.6929	0.6885	0.6806
1.6418	1.0337	1.0334	1.0341	1.0351
1.6518	0.6666	0.6687	0.6663	0.6608
1.6618	0.9226	0.9234	0.9219	0.9193
1.6718	0.9439	0.9437	0.9446	0.9452
1.6818	0.6443	0.6474	0.6426	0.6336
1.6918	1.036	1.0357	1.0362	1.0371
1.7018	0.6828	0.6847	0.6826	0.6777
1.7118	0.9235	0.9243	0.9228	0.9202
1.7218	0.9344	0.9343	0.9351	0.9356
1.7318	0.6723	0.6752	0.6706	0.6622
1.7418	1.0366	1.0362	1.037	1.0381
1.7518	0.6261	0.6287	0.6253	0.6183
1.7618	0.9797	0.98	0.9793	0.9782
1.7718	0.8505	0.8509	0.8511	0.8503
1.7818	0.7888	0.7907	0.7875	0.7818
1.7918	1.0037	1.0032	1.0043	1.0056
1.8018	0.6009	0.6043	0.5993	0.5896
1.8118	1.0358	1.0355	1.0361	1.0368
1.8218	0.6607	0.6628	0.6604	0.6548
1.8318	0.9649	0.9653	0.9645	0.963
1.8418	0.8494	0.8497	0.85	0.8493
1.8518	0.8109	0.8126	0.8097	0.8045
1.8618	0.9814	0.981	0.9821	0.9832
1.8718	0.6451	0.6482	0.6434	0.6344
1.8818	1.0353	1.0349	1.0358	1.037
1.8918	0.5874	0.5907	0.5861	0.577
1.9018	1.0304	1.0303	1.0305	1.0309
1.9118	0.67	0.6721	0.6698	0.6646
1.9218	0.9778	0.9781	0.9774	0.9762
1.9318	0.802	0.8027	0.8024	0.8008
1.9418	0.8858	0.8869	0.8849	0.8815
1.9518	0.9123	0.9123	0.913	0.9133
1.9618	0.7761	0.778	0.7747	0.7687
1.9718	0.9824	0.9821	0.9832	0.9843
1.9818	0.6806	0.6834	0.6789	0.6707
1.9918	1.0196	1.0192	1.0202	1.0216
2.0018	0.62	0.6233	0.6182	0.6087
2.0118	1.0364	1.0361	1.037	1.0383
2.0218	0.5921	0.5957	0.5905	0.5807
2.0318	1.0427	1.0423	1.0431	1.0443

2.0418	0.5836	0.5871	0.5821	0.5724
2.0518	1.0441	1.0438	1.0445	1.0456
2.0618	0.5822	0.5857	0.5808	0.5714
2.0718	1.0439	1.0437	1.0443	1.0453
2.0818	0.5813	0.5848	0.58	0.5706
2.0918	1.0435	1.0432	1.0439	1.045
2.1018	0.5791	0.5827	0.5778	0.5683
2.1118	1.043	1.0427	1.0435	1.0446
2.1218	0.5784	0.5821	0.577	0.5672
2.1318	1.041	1.0407	1.0416	1.0429
2.1418	0.5885	0.5921	0.5869	0.577
2.1518	1.0336	1.0333	1.0344	1.0357
2.1618	0.6254	0.6287	0.6237	0.6143
2.1718	1.0127	1.0124	1.0135	1.0149
2.1818	0.7027	0.7054	0.7011	0.6935
2.1918	0.9654	0.9654	0.9664	0.9674
2.2018	0.812	0.8137	0.8108	0.8057
2.2118	0.8798	0.8804	0.8807	0.8805
2.2218	0.9215	0.9224	0.9208	0.9182
2.2318	0.7582	0.7598	0.7587	0.7561
2.2418	1.0026	1.0028	1.0024	1.0018
2.2518	0.6326	0.6355	0.6323	0.6258
2.2618	1.0441	1.044	1.0444	1.0452
2.2718	0.577	0.5808	0.5756	0.5657
2.2818	1.0395	1.0393	1.0402	1.0417
2.2918	0.6646	0.6676	0.6629	0.6543
2.3018	0.9708	0.9708	0.9718	0.9729
2.3118	0.8383	0.8398	0.8372	0.8327
2.3218	0.8207	0.8217	0.8216	0.8203
2.3318	0.9827	0.9831	0.9824	0.9813
2.3418	0.6302	0.6331	0.6301	0.6236
2.3518	1.0455	1.0454	1.046	1.0469
2.3618	0.5888	0.5926	0.5872	0.5772
2.3718	1.0076	1.0075	1.0086	1.01
2.3818	0.7885	0.7904	0.7872	0.7815
2.3918	0.8427	0.8436	0.8438	0.843
2.4018	0.983	0.9834	0.9827	0.9816
2.4118	0.6098	0.613	0.6095	0.6022
2.4218	1.0487	1.0486	1.0494	1.0506
2.4318	0.643	0.6462	0.6413	0.6323
2.4418	0.9536	0.9539	0.9547	0.9556
2.4518	0.9055	0.9064	0.9047	0.9017
2.4618	0.6962	0.6984	0.6966	0.6923
2.4718	1.0459	1.0458	1.0463	1.047

2.4818	0.5957	0.5994	0.594	0.584
2.4918	0.986	0.9861	0.9871	0.9883
2.5018	0.8774	0.8785	0.8765	0.8728
2.5118	0.7134	0.7155	0.7139	0.7102
2.5218	1.0463	1.0462	1.0466	1.0474
2.5318	0.6035	0.6072	0.6018	0.5919
2.5418	0.9666	0.9668	0.9677	0.9688
2.5518	0.9161	0.917	0.9154	0.9127
2.5618	0.6489	0.6516	0.649	0.6433
2.5718	1.0513	1.0511	1.052	1.0532
2.5818	0.6849	0.6878	0.6833	0.6752
2.5918	0.876	0.8767	0.8772	0.877
2.6018	1.0002	1.0005	1.0001	0.9994
2.6118	0.5651	0.569	0.5639	0.5541
2.6218	1.0119	1.0118	1.0129	1.0144
2.6318	0.8675	0.8688	0.8666	0.8627
2.6418	0.6738	0.6762	0.6741	0.6693
2.6518	1.0526	1.0524	1.0532	1.0545
2.6618	0.7106	0.7131	0.709	0.7015
2.6718	0.8264	0.8274	0.8274	0.8264
2.6818	1.0339	1.0339	1.0341	1.0343
2.6918	0.598	0.6016	0.5962	0.5862
2.7018	0.9321	0.9324	0.9332	0.9339
2.7118	0.9874	0.9878	0.9871	0.9861
2.7218	0.5642	0.5681	0.5628	0.5528
2.7318	0.9918	0.9917	0.9928	0.9942
2.7418	0.9363	0.9371	0.9357	0.9334
2.7518	0.5806	0.5842	0.5798	0.5713
2.7618	1.0213	1.0211	1.0223	1.0239
2.7718	0.8961	0.8971	0.8952	0.892
2.7818	0.6045	0.6076	0.6041	0.5967
2.7918	1.0332	1.0329	1.0341	1.0358
2.8018	0.8761	0.8772	0.8751	0.8715
2.8118	0.6129	0.6159	0.6126	0.6057
2.8218	1.0342	1.0339	1.0351	1.0368
2.8318	0.8808	0.8819	0.8799	0.8763
2.8418	0.6001	0.6032	0.5997	0.5923
2.8518	1.0252	1.0249	1.0261	1.0278
2.8618	0.9101	0.911	0.9093	0.9065
2.8718	0.5735	0.577	0.5726	0.5639
2.8818	1.0004	1.0002	1.0014	1.0029
2.8918	0.9583	0.9588	0.9578	0.9561
2.9018	0.56	0.5638	0.5585	0.5483
2.9118	0.9472	0.9472	0.9482	0.9492

2.9218	1.013	1.0131	1.0129	1.0125
2.9318	0.607	0.6105	0.6052	0.5954
2.9418	0.848	0.8486	0.8489	0.8484
2.9518	1.0533	1.053	1.0536	1.0546
2.9618	0.7335	0.7358	0.7319	0.725

APPENDIX B1

Accepted values								
Tee	**Loop-in**	**Loop-in/Tee**	**Grid**	**Mach**	**Ratio G/M**	**STDev**	**Min**	**V Diff**
4	4	1.00	8	1.75	4.57	0.0062	0.9768	2.32%
3	4	1.33	7	1.75	4.00	0.0069	0.9741	2.59%
4	3	0.75	7	1.75	4.00	0.0069	0.974	2.60%
2	4	2.00	6	1.75	3.43	0.0078	0.9708	2.92%
3	3	1.00	6	1.75	3.43	0.0078	0.9706	2.94%
4	2	0.50	6	1.75	3.43	0.0079	0.9705	2.95%
1	4	4.00	5	1.75	2.86	0.0089	0.9664	3.36%
2	3	1.50	5	1.75	2.86	0.0089	0.9663	3.37%
3	2	0.67	5	1.75	2.86	0.0090	0.9662	3.38%
4	1	0.25	5	1.75	2.86	0.0090	0.9659	3.41%
4	4	1.00	8	3.50	2.29	0.0093	0.9561	4.39%
3	4	1.33	7	3.50	2.00	0.0100	0.9513	4.87%
4	3	0.75	7	3.50	2.00	0.0101	0.9511	4.89%
1	3	3.00	4	1.75	2.29	0.0104	0.9606	3.94%
2	2	1.00	4	1.75	2.29	0.0105	0.9604	3.96%
3	1	0.33	4	1.75	2.29	0.0105	0.9602	3.98%
1	2	2.00	3	1.75	1.71	0.0124	0.9528	4.72%
2	**1**	**0.50**	**3**	**1.75**	**1.71**	**0.0125**	**0.9526**	**4.74%**
Non-acceptable values								
2	4	2.00	6	3.50	1.71	0.0112	0.9454	5.46%
3	3	1.00	6	3.50	1.71	0.0112	0.9452	5.48%
4	2	0.50	6	3.50	1.71	0.0113	0.9449	5.51%
4	4	1.00	8	5.25	1.52	0.0117	0.9376	6.24%
3	2	0.67	5	3.50	1.43	0.0128	0.9374	6.26%
1	1	1.00	2	27.99	0.07	0.2319	0.4469	55.31%

Range 1-5kA results

APPENDIX B2

Grid 1	Grid 2	Sumg	3ph close	Mach	Gsumg/M	Gclose/M	STDdev	Min	Diff
10	10	20	17.59	1.75	11.43	10.06	0.0014	0.990	1.02%
9	10	19	16.82	1.75	10.86	9.61	0.0015	0.989	1.07%
10	9	19	16.76	1.75	10.86	9.58	0.0015	0.989	1.08%
					⇩				
10	10	20	18.35	5.25	3.81	3.50	0.0041	0.971	2.90%
8	5	13	12.16	3.50	3.72	3.47	0.0041	0.971	2.95%
9	10	19	17.57	5.25	3.62	3.35	0.0043	0.970	3.02%
10	9	19	17.51	5.25	3.62	3.34	0.0044	0.970	3.04%
7	5	12	11.73	5.25	2.29	2.24	0.0065	0.955	4.53%
6	10	16	15.53	7.00	2.29	2.22	0.0068	0.955	4.51%
9	10	19	18.27	8.75	2.17	2.09	0.0073	0.953	4.75%
10	9	19	18.21	8.75	2.17	2.08	0.0073	0.952	4.78%
9	6	15	14.54	7.00	2.14	2.08	0.0073	0.952	4.85%
10	5	15	14.46	7.00	2.14	2.07	0.0074	0.951	4.89%
5	9	14	13.87	7.00	2.00	1.98	0.0074	0.950	5.04%
8	10	18	17.49	8.75	2.06	2.00	0.0074	0.950	4.97%
6	8	14	13.85	7.00	2.00	1.98	0.0074	0.949	5.06%
9	9	18	17.44	8.75	2.06	1.99	0.0074	0.950	4.99%
7	7	14	13.81	7.00	2.00	1.97	0.0074	0.949	5.09%
10	**8**	**18**	**17.37**	**8.75**	**2.06**	**1.99**	**0.0075**	**0.950**	**5.02%**

Range 5-10kA results *(Non-accepted values omitted)*

APPENDIX B3

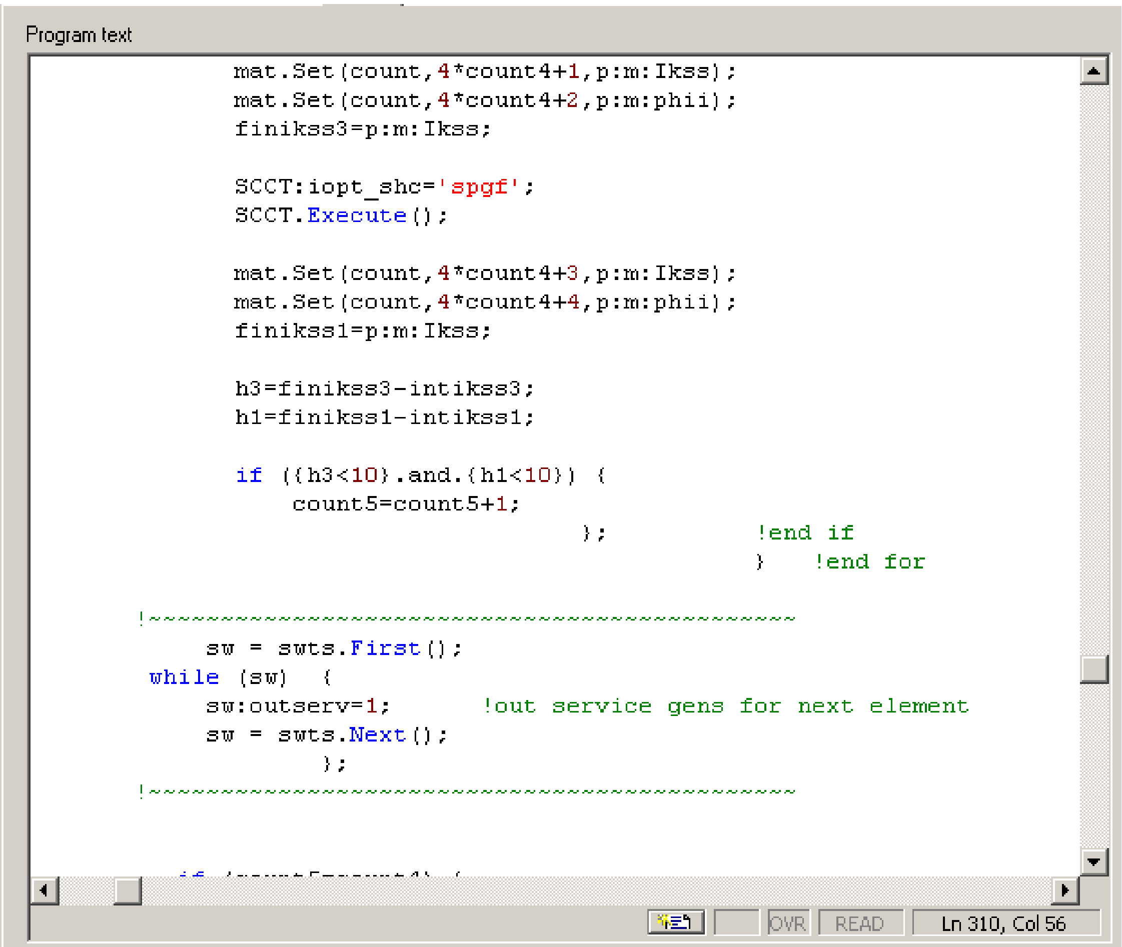
Grid 1	Grid 2	Sumg	Mach	3 ph close	Sumg/M	3ph close/M	Stddev	Min	Diff
15	15	30	1.75	25.41	17.14	14.52	0.000952	0.993	0.70%
14	15	29	1.75	24.69	16.57	14.11	0.000983	0.9928	0.72%
15	14	29	1.75	24.60	16.57	14.06	0.000991	0.9927	0.73%
13	15	28	1.75	23.96	16.00	13.69	0.001014	0.9926	0.74%
14	14	28	1.75	23.88	16.00	13.65	0.001024	0.9925	0.75%
15	13	28	1.75	23.79	16.00	13.59	0.001025	0.9925	0.75%
10	15	25	1.75	21.69	14.29	12.40	0.00112	0.9918	0.82%
13	15	28	3.5	24.34	8.00	6.95	0.002028	0.9855	1.45%
14	14	28	3.5	24.26	8.00	6.93	0.002036	0.9854	1.46%
					⬇				
10	15	25	7	22.79	3.57	3.26	0.004427	0.9695	3.05%
11	14	25	7	22.75	3.57	3.25	0.004444	0.9694	3.06%
12	13	25	7	22.69	3.57	3.24	0.00447	0.9693	3.07%
13	12	25	7	22.62	3.57	3.23	0.004495	0.9691	3.09%
14	11	25	7	22.52	3.57	3.22	0.004526	0.9689	3.11%
15	10	25	7	22.41	3.57	3.20	0.004554	0.9687	3.13%
14	10	24	7	21.69	3.43	3.10	0.00471	0.9676	3.24%
10	13	23	7	21.18	3.29	3.03	0.004789	0.9671	3.29%
11	12	23	7	21.12	3.29	3.02	0.00482	0.9669	3.31%
12	11	23	7	21.05	3.29	3.01	0.004843	0.9667	3.33%
15	15	30	8.75	26.83	3.43	3.07	0.004867	0.968	3.20%
					⬇				
11	15	26	12.25	24.52	2.12	2.00	0.007645	0.9519	4.81%
10	15	25	12.25	23.76	2.04	1.94	0.00766	0.9504	4.96%
12	14	26	12.25	24.47	2.12	2.00	0.007684	0.9517	4.83%
15	15	30	14	27.75	2.14	1.98	0.007686	0.952	4.80%
12	10	22	10.5	20.89	2.10	1.99	0.007689	0.9506	4.94%
11	14	25	12.25	23.72	2.04	1.94	0.007695	0.9502	4.98%
13	**13**	**26**	**12.25**	**24.40**	**2.12**	**1.99**	**0.007721**	**0.9515**	**4.85%**

Range 10-15kA results *(Non-accepted values omitted)*

APPENDIX C

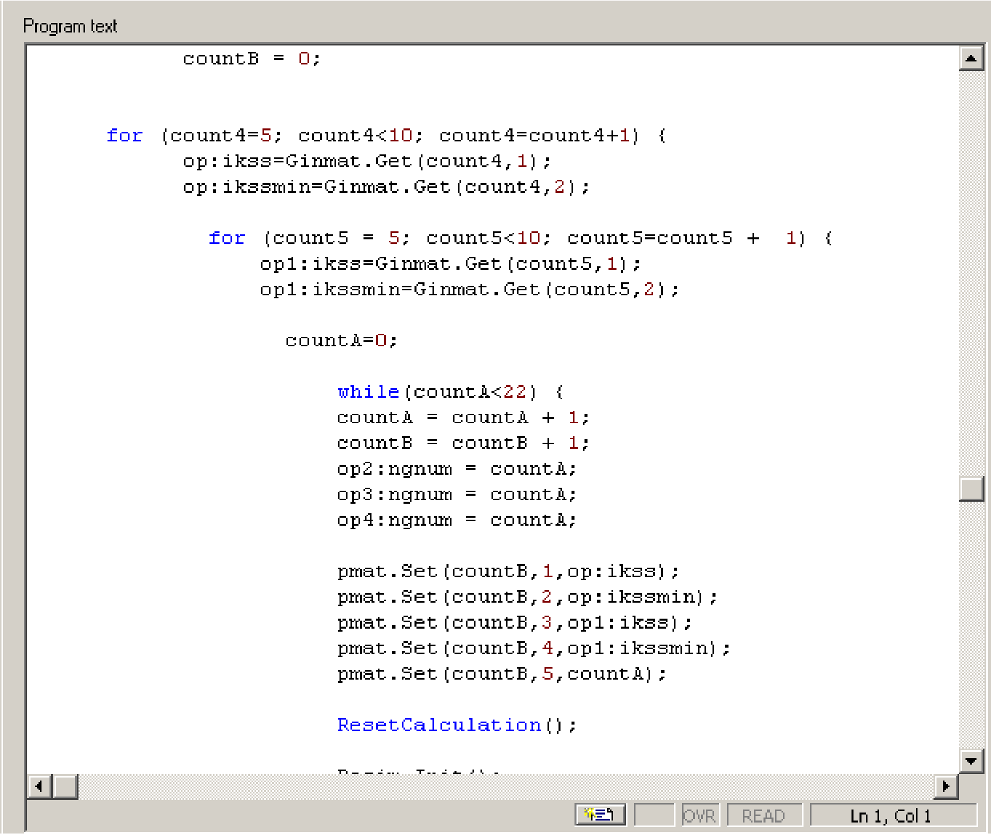
DIgSILENT Powerfactory screen dumps for relevant controls

C.1: DPL screen dump: Penetration paths



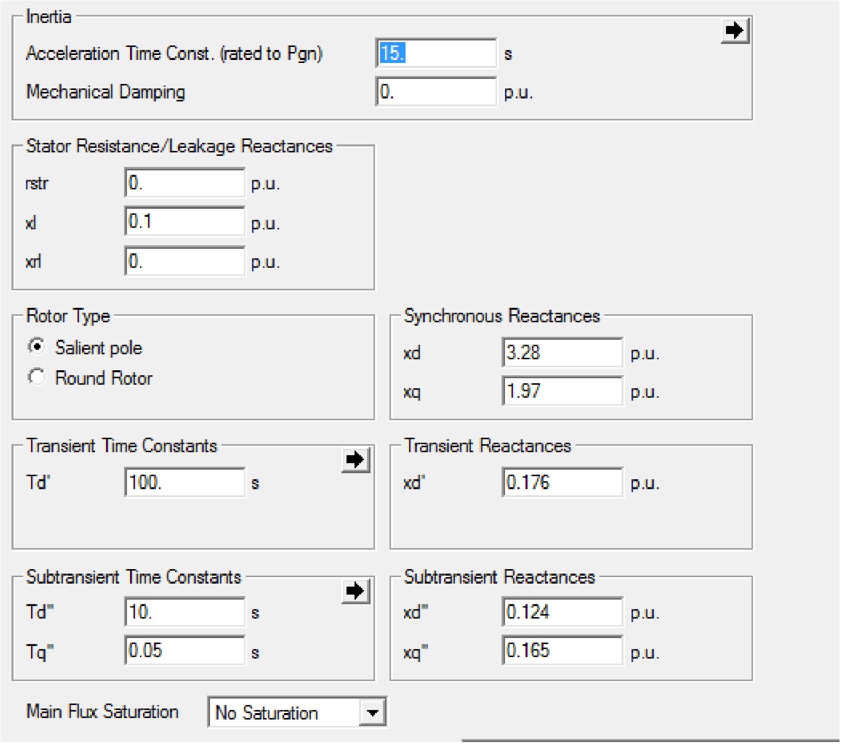
```
       mat.Set(count,4*count4+1,p:m:Ikss);
       mat.Set(count,4*count4+2,p:m:phii);
       finikss3=p:m:Ikss;

       SCCT:iopt_shc='spgf';
       SCCT.Execute();

       mat.Set(count,4*count4+3,p:m:Ikss);
       mat.Set(count,4*count4+4,p:m:phii);
       finikss1=p:m:Ikss;

       h3=finikss3-intikss3;
       h1=finikss1-intikss1;

       if ((h3<10).and.(h1<10)) {
           count5=count5+1;
                               };          !end if
                                           }   !end for

!~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
     sw = swts.First();
 while (sw)  {
     sw:outserv=1;      !out service gens for next element
     sw = swts.Next();
             };
!~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
```

C.2: DPL screen dump: Voltage Stability



```
      countB = 0;


for (count4=5; count4<10; count4=count4+1) {
      op:ikss=Ginmat.Get(count4,1);
      op:ikssmin=Ginmat.Get(count4,2);

        for (count5 = 5; count5<10; count5=count5 +  1) {
            op1:ikss=Ginmat.Get(count5,1);
            op1:ikssmin=Ginmat.Get(count5,2);

              countA=0;

                  while(countA<22) {
                  countA = countA + 1;
                  countB = countB + 1;
                  op2:ngnum = countA;
                  op3:ngnum = countA;
                  op4:ngnum = countA;

                  pmat.Set(countB,1,op:ikss);
                  pmat.Set(countB,2,op:ikssmin);
                  pmat.Set(countB,3,op1:ikss);
                  pmat.Set(countB,4,op1:ikssmin);
                  pmat.Set(countB,5,countA);

                  ResetCalculation();
```

C.3: DPL screen dump: Generic generator model inputs



Inertia

Acceleration Time Const. (rated to Pgn) 15. s

Mechanical Damping 0. p.u.

Stator Resistance/Leakage Reactances

rstr 0. p.u.

xl 0.1 p.u.

xrl 0. p.u.

Rotor Type

● Salient pole

○ Round Rotor

Synchronous Reactances

xd 3.28 p.u.

xq 1.97 p.u.

Transient Time Constants

Td' 100. s

Transient Reactances

xd' 0.176 p.u.

Subtransient Time Constants

Td'' 10. s

Tq'' 0.05 s

Subtransient Reactances

xd'' 0.124 p.u.

xq'' 0.165 p.u.

Main Flux Saturation: No Saturation