

Power System Grid Planning with Distributed Generation



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Key Words: Power system, Grid planning, Distributed Generation, Wind, Solar.

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Synopsis

Distributed Generation (DG) is one of the technologies approved by the South African government for the country's generation expansion to meet future load demand and to support economic growth. DGs change the conventional power flow (generation, transmission to distribution) by injecting real and reactive power at distribution voltage levels. The change in the conventional power flow creates complexity in the power system grid planning due to the conversion of the power system from a passive network to an active network. Introduction of bi-directional power flow on the power system can, among other benefits reduce local power demand which opens opportunities for capital investment deferrals on the transmission and distribution sectors.

Consequently, DG impact on the transmission and distribution grid planning has been studied by other researchers. However, previous studies evaluated DG integration on a regulated market and assumed a certain level of generation availability during network peaking period. None of the studies have yet evaluated the benefits on an unregulated market using real measured data. Furthermore, SA distribution network expansion is also being planned without incorporating DGs on the network because of unreliability of wind and solar energy and the network operator's inability to influence the size, location and penetration level of DGs. This planning approach forces the network operator to do more to ensure high network strength. This approach can also result in network overdesign and unnecessary capital expenditure due to the potential benefits that can be deduced from DGs. This dissertation therefore aims to investigate whether incorporating future DG integration in distribution network planning can alleviate financial ramifications of grid code compliance requirements.

The data used in the simulations was obtained from the distribution network operator and comprises of both real and reactive power values with a sampling time of 60 minutes for a period of a year. Simulations were conducted for both low and high load conditions to cover the extreme ends of the network and the parameters that were assessed are thermal rating, voltage regulation and network grid losses. Results showed that thermal constraints that are expected on the network when DGs are not considered are not evident when DGs are considered. Results further revealed that there are undervoltage improvements on the network when DGs are considered, and this reduces the capital expenditure that would have otherwise been incurred without DGs to result in a grid code compliant network.

Furthermore, there is evidence of reduction in losses under high load conditions and increase in losses under low load conditions in the simulation results. Reduction in losses is caused by supplementary generation from wind and solar plants while increase in losses is due to excessive generation from wind plants which necessitate transportation over long distances to the nearest load centres. In addition to location, size and penetration levels as described in the literature, technology selection for a particular load type is also of utmost important to maximise the DG benefits on the network.

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List of Acronyms

IRP-Integrated Resource Plan

DG -Distributed Generation

SDP-Spatial Development Plan

BESS- Battery Energy Storage System

DC-Direct Current

AC-Alternative Current

DFIG-Double Fed Induction Generator

SCIG-Squirrel Cage Induction Generator

WRIG-Wound Rotor Induction Generator

WTG-Wind Turbine Generator

PV-Photovoltaic

KW-Kilowatts

MW-Megawatts

LPU-Large Power User

SPU-Small Power User

SA-South Africa

IEEE-Institution of Electrical and Electronic Engineers

DNO-Distribution Network Operator

CSP-Concentrated Solar Power

EHV-Extra High Voltage

AF-Availability Factor

SSEG- Small Scale Embedded Generation

1 INTRODUCTION

1.1 Background and motivation

The reliability of South Africa's generation fleet has deteriorated over the years due to the ageing plants that started operating at maximum. The South African load demand has also been increasing to a point that the available generation fleet is at times unable to fully support the load demand. This has resulted in a state owned utility, Eskom, to implement load shedding when necessary since 2008 to protect the power system from grid collapse [51]. Implementation of load shedding in 2008 revealed the need for a long term generation expansion plan for the country to cater for the ever increasing load demand and to support the economic growth. This resulted in the establishment of Integrated Resource Plan (IRP) which was first published in 2010. IRP is an electrical infrastructure development plan based on the least-cost electricity supply and demand balance, taking into consideration the environment, security and reliability of supply. The IRP document gets revised on a periodic basis and the latest revision (IRP 2019) shows that a total of approximately 78 GW of generation will be installed by year 2030. The generation is anticipated to be a mixture of different technologies including but not limited to Nuclear, Coal and Distributed Generation (DG) [52].

The planned generation will require reliable transmission and distribution networks with adequate capabilities to evacuate the generated capacity to different load centres throughout the country. In parallel with the generation fleet expansion, the transmission and distribution networks also require strengthening to cater for generation expansion as well as load demand. However, introduction of DGs create complexity in the power system grid planning due to the conversion of the power system from a passive network to an active network. The power flow changes from its conventional form (generation, transmission to distribution) to an active form where real and reactive power also gets injected on the distribution voltage levels. Introduction of DGs closer to the load centres can, among other benefits reduce local power demand requirements from the upstream networks which opens up opportunities for capital investment deferrals in the transmission and distribution sectors[1]-[3].

Consequently, distributed generation impact on the transmission and distribution grid planning has been studied by other researchers [1]-[10]. Results from the studies showed that DGs can be used as one of the alternative solutions on the transmission and distribution system infrastructure planning process to provide many benefits such as reduction in power losses, voltage regulation improvements and capital investment deferrals. However, previous researchers strategically placed DGs on the study networks to assess the benefits, thereby assuming a regulated market where the network operator is able to influence the location, size and penetration levels of DGs. This is currently not the case in South Africa (SA) as DGs which are predominantly wind and solar are either customer driven or Department of Energy (DoE) driven and as a result, they can be anywhere on the network. Previous studies have

not yet assessed a scenario where the market is unregulated. In addition, previous studies strategically increased the DG sizes on different nodes to deduce the potential benefits, thereby assuming a certain level of distributed generation availability during the network peaking period. Due to the intermittent nature of wind and solar energy resources, availability of distributed generation deduced theoretically is not always guaranteed in reality. However, none of the studies have yet evaluated the benefits of DGs using real measured data.

Furthermore, SA distribution network expansion is being planned without incorporating the existing or planned DGs to guarantee high network strength due to the unreliability of wind and solar energy and the network operator's inability to influence the size, location and penetration level of DGs. This approach can however result in network overdesign and unnecessary capital expenditure due to the potential benefits that can be deduced from distributed generation when considered in the power system grid planning process.

It is therefore hypothesized that *"incorporating future DG integration in distribution network planning can alleviate the financial ramifications of grid code compliance requirements"*. This dissertation aims to investigate the impact of DGs on the SA power system grid planning. Research focus will be on capital investment deferral benefits on an unregulated network.

1.2 Research Questions

The hypothesis will be tested using the following questions:

- How do DGs assist the power system to comply with the grid code?
- Can the DG benefits that are realised in regulated markets be realised in unregulated markets?
- How does a DG integration in distribution network planning impact the capital investment required to result in a grid code compliant network?

1.3 Report Objectives

The objectives of a study are therefore to:

- Conduct literature review on power system grid planning and distributed generation.
- Review in detail the impact that distributed generation has on transmission and distribution network planning.
- Evaluate whether the DG benefits deduced on a regulated market can also be obtained from an unregulated market.
- Analyze the availability of DGs in relation to the network load requirements to allow for future DG impact analysis.
- Investigate whether incorporating future DG integration in distribution network planning can alleviate the financial ramifications of grid code compliance requirements.

1.4 Scope and limitations

This report will investigate the impact of distributed generation on power system grid planning using a section of the SA distribution network due to easy access to the relevant data required for the analysis. The distributed generation technologies will only be limited to Solar and Wind due to them being the most common DGs on the SA network. The analysis will be done over a 10 year study horizon due to it being a typical study period for distribution networks.

Furthermore, forecasting will not form part of the study due to limited time frame. The 10 year load forecast that has already been compiled by the network operator for the study area will be used. The network operator currently does not perform distributed generation forecast on the distribution network due to intermittent nature of wind and solar resources. Therefore, reasonable assumptions will be made to predict generation availability for future studies within the study horizon.

1.5 Plan of Development

The structure of the report is as follows.

Chapter 1

A brief introduction which introduces the title of the report is given. An overview about the purpose of the report is provided. Research topic is briefly discussed and the expected objectives are stated.

Chapter 2

An overview of power system grid planning and power system planning process is given. DGs namely wind and solar energy are discussed. Benefits and challenges of DGs are given and the impact of DGs on power system grid planning is discussed.

Chapter 3

The methodology used to assess the impact of DGs on South Africa's power system grid planning is discussed. This includes software selection, study network and its parameters, assumptions made and the procedure followed.

Chapter 4

Results are presented and analysed in detail.

Chapter 5

Conclusions are drawn based on the findings and discussion of the results.

Chapter 6

Recommendations are made based on the conclusions of the report.

References

List of references used in the report are provided.

Appendix

Appendices

2 LITERATURE REVIEW

2.1 Introduction

Chapter two discusses a comprehensive literature review on the impact of distributed generation on power system planning and analysis. Included in this chapter is the power system overview, power system components, power system planning, detailed discussions on DGs particularly Wind and Solar energy, benefits and challenges of DGs and the impact of DGs on capital investment deferral at both transmission and distribution level.

2.2 Power system overview

Electric power systems are traditionally designed on the principle of power production in central power generation stations and its power delivery to the end user through transmission and distribution networks. This traditional system comprises of three parts namely Generation, Transmission and Distribution. The role of generation is to produce electricity by transforming one source of energy into electrical energy. Transmission component acts as an interface between generation and distribution. Its role is to transfer power over long distances to realise economic and system benefits such as reduction in power losses which in turn increases system efficiency. The distribution component is an interface between transmission and the end user and its main function is to bring electricity to the end user through electrical distribution delivery infrastructure [11].

2.3 Power system components

The basic components of a power system are generators, circuit breakers, transformers, transmission and distribution lines, buses and loads. A function of each component is given below [12]:

- **Generators**-convert mechanical power into electrical power for transportation by both transmission and distribution systems to load centres.
- **Circuit breakers**- interrupt power flow either temporary or permanently under emergency conditions to ensure safe operation of the power system.
- **Transformers**-step up or down voltage within the power system network.
- **Transmission and distribution lines**- the lines are used to transport electric power from one location to another.
- **Buses**- these are nodes where several lines or power system components are connected.
- **Load**- consumers of electric power.

A schematic diagram of the power supply system is shown in Figure 2.1.

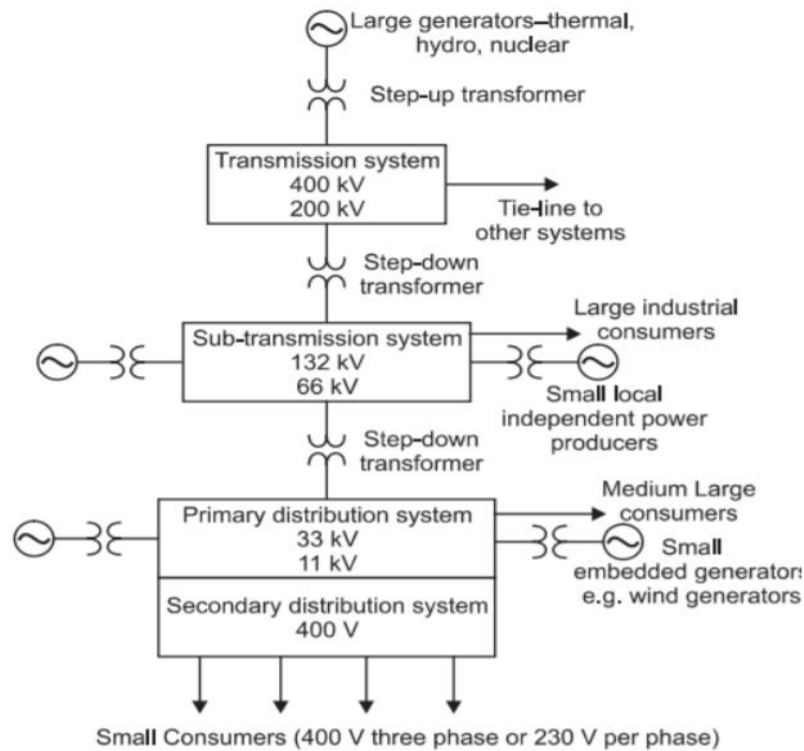


Figure 2.1: A schematic diagram of a traditional power system[12]

A power system is planned and designed to cover a pre-defined electric supply area. The above components are strategically (based on planning and design requirements) placed throughout the geographical area within the electric supply boundaries to serve the functions as described above. A proper coordination between the above mentioned components is required to ensure compliance of the power system to the prescribed limits in the grid code. This coordination is realised through power system planning.

2.4 Power system planning

2.4.1 An overview

Power system planning is essentially a prediction of how the system will grow over a specific period of time from a load perspective, based on certain assumptions about future load developments. The prediction of future load assists with decision making on the size of investment that is required at a generation, transmission as well as distribution level. Consequently, plans at each level are formulated on the basis of anticipated load in the future. However, these plans need to be reviewed periodically as some of them can become technically and economically obsolete due to uncertainties within the power system planning environment. These uncertainties include but are not limited to new inventions in the electrical utilisation equipment or unforeseen residential, commercial and industrial

projects that can drastically change the predicted future load which in turn invalidate the plans that have already been formulated and evaluated [13].

2.4.2 Power system planning process

The main steps in the power system planning process can be summarised as follows [14]-[15]:

- **Data gathering and analysis-** this is the first step of preparing for power system planning. Included in this step is identification of boundaries for the study area, analysis of load type (residential, industrial, agricultural, etc) within the study area, review of historical load profiles for different customer classes within the study area in order to determine the dominating sector in terms of load consumption, sensitivity analysis of different load patterns to external factors such as political and economic changes, review of Spatial Development Plans (SDP) for the area and the expected phasing of the developments.
- **Prepare for Network Planning-** following gathering of relevant and accurate information that serves as a base for the study area, a development of the as-is electrical network spatial model is required together with analysis of the network capabilities both under normal and emergency conditions using the relevant tool.
- **Develop forecast-** this is a realistic prediction of the generation capacity and electrical load for the supply area, over a medium to long term period which is typically 3 to 20 years. There are different forecasting techniques that can be utilised for medium to long term forecasting and selection of the technique is dependent on many factors including but not limited to availability of data which acts as an input to the forecast. Generally, geo-based forecasting is regarded as the most suitable method for long term electrical generation capacity and load forecasting. The load prediction is done on a geographic basis using geographical data as a backdrop information and input data, as well as geographically predicting where and how the generation capacity and load will increase over a specified study horizon.
- **Review network condition and performance-** analysis of age, condition and performance of different equipment within the study area in order to identify which equipment needs to be decommissioned and replaced.
- **Perform simulations-** use of demand and supply forecast information to predict the network performance over a specified period of time using the relevant simulation tools in order to identify both existing and future constraints within the study area. Parameters that are studied include thermal rating of the equipment, minimum and maximum voltages, technical losses and fault levels.
- **Perform Strategic Network Planning-** following identification of both existing and future problems; this step uses information from the simulations to produce a long term plan that aims to bridge the gap between the current network and future network requirements. This is

done by proposing different alternatives and evaluating them both technically and financially taking into account the network condition and performance, environmental, operational and implementation considerations in order to ensure executable and high network strength.

In a traditional power system planning, the above process is performed by a regulated power utility. However, the restructuring and deregulation of the global power market has introduced changes to the power system planning practices. These changes include but are not limited to introduction of DGs.

2.4.3 Distributed Generation

2.4.3.1 Overview

Distributed Generation, sometimes also known as Dispersed Generation or Embedded Generation is a decentralised generation of electricity near its point of use rather than transmitting power over an electrical grid to the end user from a large centralized facility such as Nuclear Power Plant .The DG concept refers to a variety of technologies that generate electricity at or near its point of use. These technologies include solar photovoltaic systems, wind systems, combined heat and power systems, etc. They may serve a single structure such as a residential home or business, form part of the microgrid and can service a military base [16], [46]-[47]. The difference between centralized generation and decentralized generation is shown in Figure 2.2.

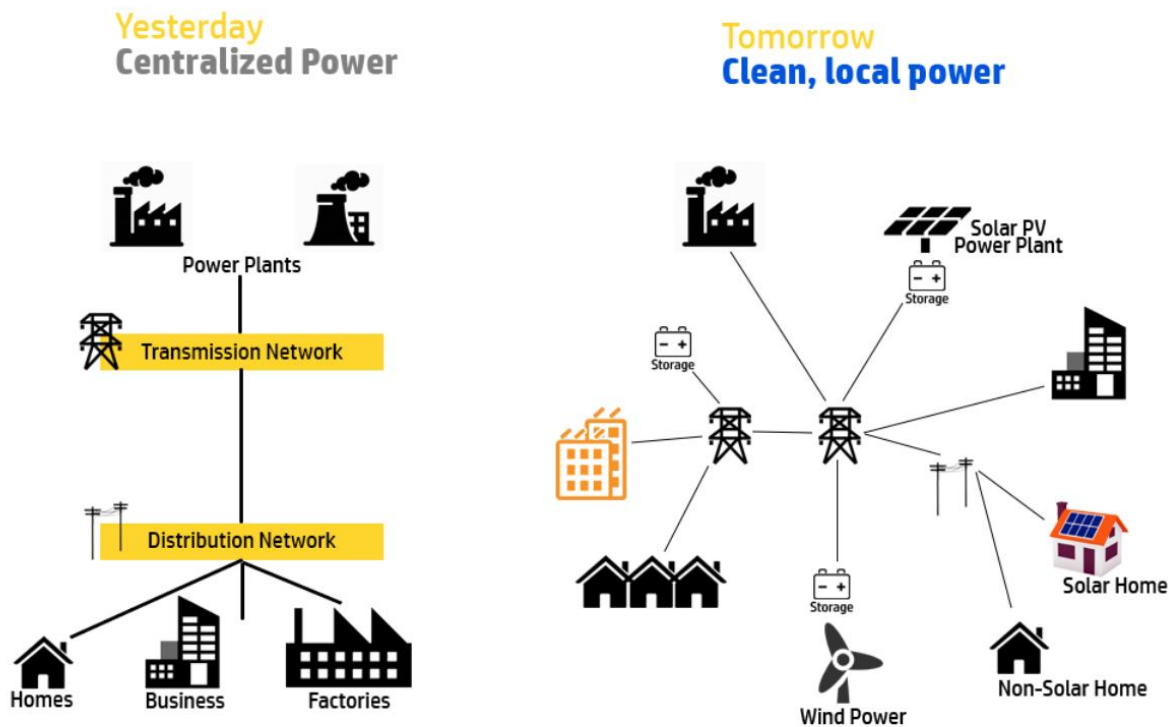


Figure 2.2: Centralized and decentralized generation [48]

DGs consist of power generators of smaller units embedded within the distribution network, thus converting the power grid from a passive to an active network. The plant can either be connected on the consumer's side of the meter or to the utility's distribution system and this is illustrated in Figure 2.3.

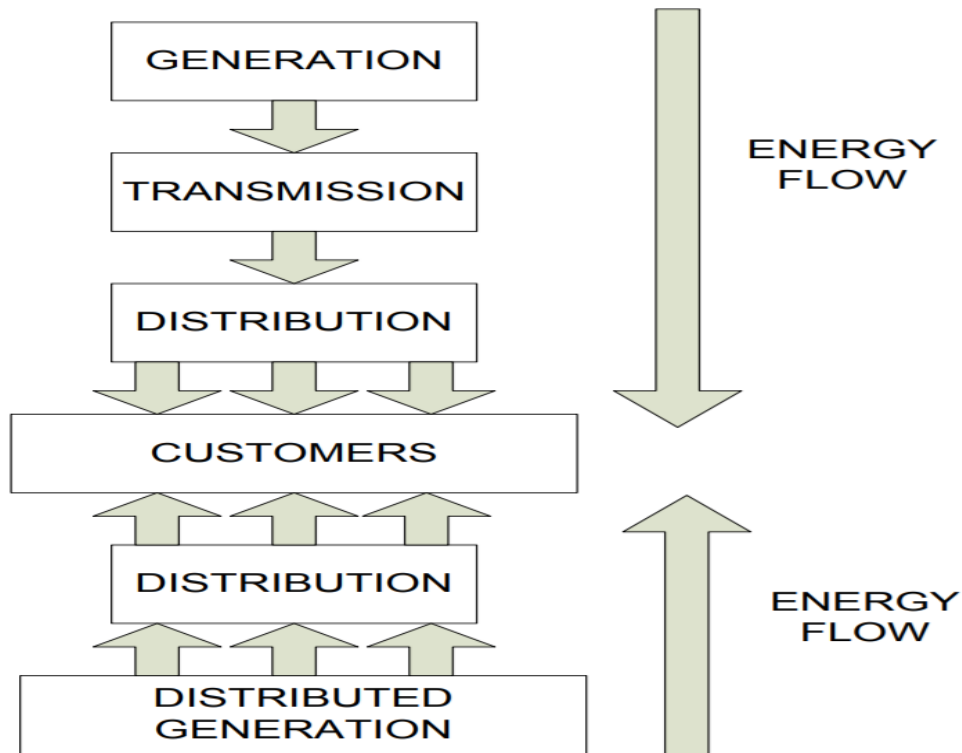


Figure 2.3: Centralized and decentralized generation [17]

This is an alternative to the production of electricity in large centralized plants. Although centralized generation has always been the most cost effective and attractive investment option for providing modern energy access, maturing technologies and declining costs are shifting the electricity provision model towards a future where DGs have a potential to play an important role within the broader power sector environment. This technology is highly scalable and can be deployed rapidly to support many countries' development goal which is to increase energy access while protecting the environment [18].

2.4.3.2 Classification of Distributed Generation

DGs can be classified according to the supply duration, capacity, generated power and technology type. Figure 2.4 below shows the classification of DGs according to the categories described above.

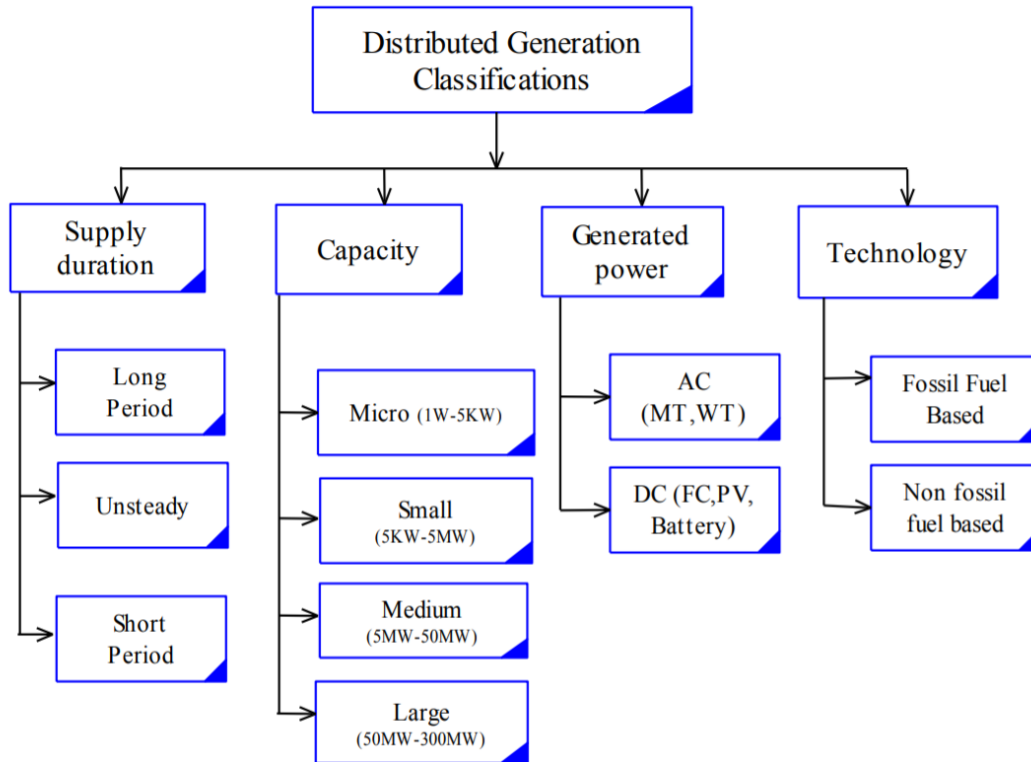


Figure 2.4: Classification of DGs[19]

Classification according to supply duration

DGs can be classified based on their power supply period which can be divided into short, unsteady and long period supply. Short period DGs are used for supply continuity by making supply available at the time of need for only a short period of time. An example includes Battery Energy Storage Systems (BESS). Unsteady DGs are weather dependent and include Wind and Solar energy. Long period DGs include Gas Turbines and are used as base load stations [19]-[20].

Classification according to capacity

DGs are available in different sizes ranging from micro (1 W-5 kW) to DGs as large as 300 MW. The capacities are not restrictedly defined due to dependence on the use type (utility or customer) and application [19]-[20].

Classification according to generated power

The electrical current output of the DG can either be Direct Current (DC) or Alternating Current (AC) depending on the application. The difference between DC and AC is that, DC only flows in one direction while AC changes direction periodically [19]-[20].

Classification according to technology

DGs can either be fossil or non-fossil fuel based as shown in Figure 2.4. Fossil fuel technologies include Micro Turbines and Fuel Cells. Non-Fossil fuel technologies include storage devices and renewable energy devices [19]-[20]. There are different types of renewable energy devices however; the scope of this research is only limited to wind and solar energy due to the predominance of these technologies on the SA network. Consequently, only wind and solar technologies will be discussed further.

2.4.4 Wind energy

2.4.4.1 Overview

Wind energy generation is the process of creating electricity using wind as a primary source. It is one of the fastest growing renewable energy technologies and the usage is on the rise worldwide due to declining costs. The installed wind generation capacity worldwide has increased from 7.5 GW in 1997 to about 564 GW in 2018. In addition, electricity production from wind doubled between 2009 and 2013 and wind energy accounted for about 16% of the electricity generated by renewable energy technologies. Wind generation plants can either be offshore or onshore. In offshore systems, the wind blows from the land towards the sea while it is the opposite in onshore systems. Offshore systems tend to be more efficient than onshore systems due to a more consistent wind speed and direction and fewer turbines are needed to provide the same amount of power compared to onshore systems [21]-[22].

2.4.4.2 Components and Operation

Wind energy systems consist of several components. These components propel operation of a wind energy system. Essentially, the wind flow past the wind turbine blades and as soon as the wind blows over the wind turbine blades, the blades lift and rotate. The rotating blades turn a shaft that is connected to a wind turbine generator. The rotating shaft causes the generator to produce electricity as it turns. The anticipated energy output of a typical wind turbine over an annual period is often expressed as the wind turbine capacity factor. The formula for the capacity factor is shown below [24]:

$$\text{Capacity factor} = \frac{\text{Actual annual energy produced}}{\text{Energy produced over an annual period at full output constantly}} \dots\dots\dots (2.1)$$

Figure 2.5 below shows the components of a typical wind energy system.

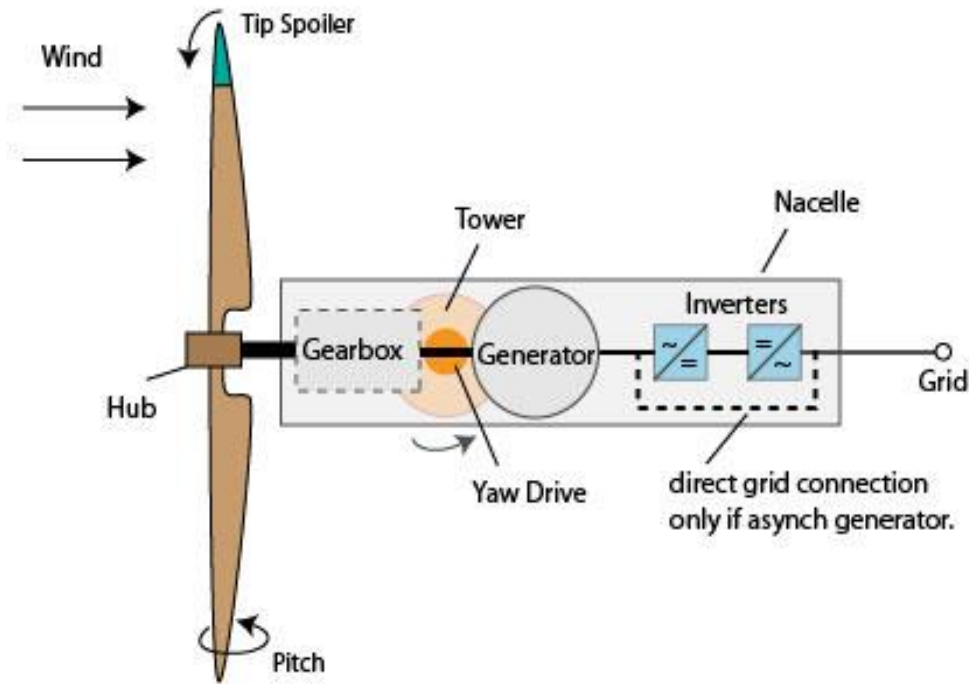


Figure 2.5: Wind energy system components [49]

2.4.4.3 Classification of Wind Turbines

Classification by configuration

There are different types of wind turbine configurations in operation. However, the most used device is the horizontal axis wind turbine. This turbine comprises of only a few aerodynamically optimised rotor blades and can deliver power ranging from 10 kW to a few MW. The largest turbine available in the European market is 8MW and bigger machines are currently in the development phase. This turbine has a very high efficiency. Consequently, it is mostly used for electricity generation which needs high speed engines to keep the generator and gear transmission small and cheap. Furthermore, another horizontal type is the multiblade wind turbine. Such wind turbines have a high starting torque and low rotation numbers which makes them suitable for driving mechanical water pumps [25].

In addition to the horizontal design, another type of turbine is a vertical axis construction which comprises of two categories namely Darrieus and Savonius. Darrieus type design is independent of wind direction. However, a generator working as a motor is required for start-up. In addition, they are very noisy compared to horizontal type designs and the wind vertical locality increases significantly with height which makes horizontal axis wheel on towers more economical. The Savonius design is only used for research to perform activities such as wind velocity measurements and is not suitable for power or electricity production [25].

Another wind turbine design type is what is known as Up-Stream Power Station or thermal tower. Essentially, this can be regarded as a mix between a wind turbine and a solar collector. At the top, the high tower is wind wheel on a vertical axis driven by the rising warm air. The warm air is due to the solar collector which is installed around the footing of the tower. The collector design is very simple and comprises of a transparent plastic foil that is fixed over several metres on the ground in a circle around the tower. This configuration requires a lot of space at the station and the tower has to be very high. Such a system results in a poor efficiency which is estimated at only one percent. As a result, this design is hardly used [25]. The wind turbine types that have been discussed above are shown graphically in Figure 2.6.

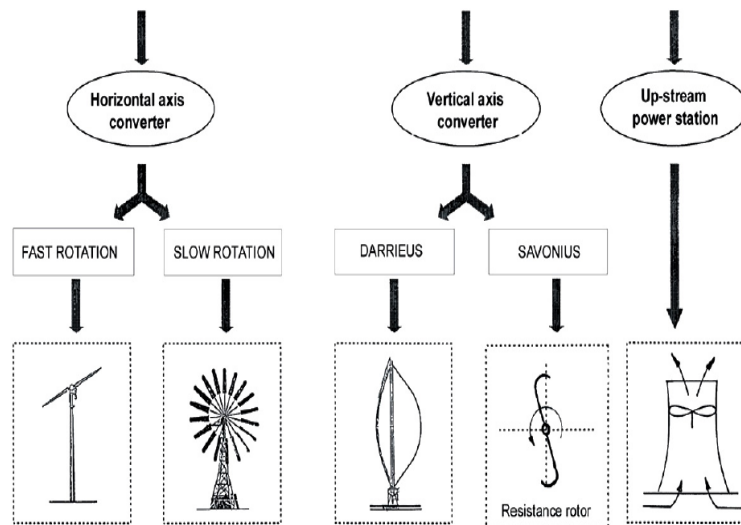


Figure 2.6: Different Wind Turbine types [25]

Classification by technology

Wind turbines comprise of different technologies which are differentiated by their generators and control techniques used to extract maximum power from the wind to inject it into the grid. The generators used can either be synchronous or asynchronous generators. Synchronous generators operate at synchronous speed N_s (rotor speed and supply frequency are the same) and can operate in both leading and lagging power factor to regulate the voltage within the system. These generators can therefore be regarded as either a sink or source of reactive power [26]. The synchronous speed is given by the following equation.

$$N_s = \frac{120f}{p} \dots\dots\dots(2.2)$$

where ;

f-frequency

p-pole number

Asynchronous generators also known as Induction generators perform the same function as synchronous generators. However, the energy is only produced when the rotor is turned faster than the synchronous speed. Asynchronous machines are generally preferred than synchronous machines due to their cost, robustness, size, simplicity, high efficiency and reliability. However, its operation is not possible without a three phase main supply due to the need to consume reactive power from the grid to start-up. Consequently, these generators cannot be easily used as back up units. The generators' ability to produce energy at varying rotor speed makes them favourable in Wind Energy Farms (WEF) [26].

That said, different generators employed in wind turbines include Double Fed Induction Generator (DFIG), Squirrel Cage Induction Generator (SCIG), Wound Rotor Induction Generator (WRIG) and fully rated convertor coupled to a generator. DFIG has its torque controlled fully by an electronic converter. The generator comprises of a three-phase wound stator design, connected to the grid. Its rotor windings are externally accessible through a set of slip rings and brushes. The rotor connections may be connected to a power electronic or voltage source converter which can vary the magnitude and frequency of the rotor winding voltage. The generator consists of a control system that controls the rotor currents to change the active and reactive power output of the generator, as required. The frequency of the current injected in the rotor windings is variable, resulting in the electrical and mechanical frequencies being decoupled [26].

SCIG, also known as a fixed speed induction generator, uses a gearbox to couple the turbine to the generator. The generator stator windings are connected to the grid, resulting in the network providing excitation voltage. The turbine speed is determined by the network grid frequency, the number of pole pairs of the generator, the machine slip and the ratio of the gearbox. This type of wind generator consumes reactive power from the grid. This is an undesirable behaviour, especially in a weak network. However, this situation is typically compensated for by using capacitors connected on the generator. In addition, the reactive power is dependent on the turbine speed and it is therefore continuously changing. The variation in reactive power can cause the voltage at the wind to sag and flicker [26].

WRIG utilises their ability to store the varying incoming wind power as rotational energy, by changing the wind turbine speed. This results in a reduced mechanical stress and smoother electrical output power. The speed of the generator is decided by the grid frequency and its excitation by the electrical grid. Furthermore, there is also a dynamic slip control which is used to increase the resistance of the rotor during moment peaks (i.e. gusts). The converter coupled system has its generator connected to a full scale power converter. A wide range of electrical generators (i.e WRIG, PMIG, etc.) could be employed in a converter coupled configuration. The generator and grid frequencies are decoupled using a voltage-source converter [26]. A comparison of Wind Turbine Generators (WTG) is illustrated in Table 2.1.

Table 2.1: Comparison of different WTGs [27]

Parameter		Squirrel Cage Induction Generator	Wound Rotor Induction Generator	Doubly Fed Induction Generator	Fully scaled converter - Direct-drive with WRSG and geared WRSG	Fully scaled converter - Direct-drive with PMSG and semi-geared PMSG
Construction complexity		Least	Less	High	Highest	Higher
Aerodynamic efficiency		Least	Better	Best	Best	Best
Size (for similar capacity)		Small	Large	Larger	Largest	Between Type-3 and Type-4
Drive train efficiency (approximate)		89%	89%	89%	90%	93%
Top Head Mass (THM)		100%	100%	100%	150%	130%
Manufacturing cost (approximate)		100%	102%	103%	110%	105%
PEC cost		Less	More	High	Most expensive	Most expensive
Synchronization off WPP with grid connection		Not required	More	Not required	Required	Required
Voltage control		Poor	Marginally better	Much better	Best	Best
Reactive power control		Poor	Poor	Good	Best	Best
Noise from blades		Controlled	Controlled	Controlled	Controlled	Controlled
Energy efficiency	Viability of speed	Poor	Improved	Better	Best	Best
	Gearbox	Poor	Improved	Best	No gearbox (good for semi-geared)	No gearbox (good for semi-geared)
	Generator	Good	Better	Best	Best	Best
	Power electronics	Hardly any losses	Less losses	More losses	Most losses	Most losses
Reliability and maintenance	Slip rings and brushes	Most reliable	Less reliable	Less reliable	Less reliable	Most reliable
	Heavy gearbox	Less reliable	Less reliable	Less reliable	No gearbox (for dynamic gearbox more reliable)	No gearbox (for dynamic gearbox more reliable)
	Mechanical Stress	More	More	Less	Least	Least
	Heavy and large generator	Large (1 m to 1.75 m dia.)	Large (1 m to 1.75 m dia.)	Large (1 m to 1.75 m dia.)	Large (3 m to 10 m dia.)	Large (2 m to 5 m dia.)
Grid power Quality	Complexity of generator	Most simple	Little complex	More complex	Most complex	More complex
	Flicker	Yes	Yes	No	No	No
	Grid voltage and frequency control possibility	No	No	Yes	Yes	Yes
Grid faults	Harmonics	No	No	Not much	Not much	Not much
	Supplied fault currents	No	No	Yes	Yes to same limit	Yes to same limit
	Restores voltage	No	No	Yes	Yes	Yes

Overall, the most widely used generators are SCIG and DFIG. The power conversion technique using SCIG is widely accepted in fixed speed applications with very minimal emphasis on the power flow control and high efficiency. However, the direct connection to the grid enables the speed to vary in a very narrow range which in turn limits the wind turbine utilisation and power output. In addition, the

external reactive power compensator required for SCIG to hold distribution line voltage and prevent system overloading is another major concern. DFIG on the other hand provides high efficiency and improved power quality which makes it favourable in large-scale power conversion applications [27]-[28].

2.4.4.4 Advantages and disadvantages of wind energy

Advantages

The advantages of wind energy are [29]:

- Unlike power plants that are relying on combustion of fossil fuels, wind energy is a clean and environmental friendly fuel source with no emission of greenhouse gases.
- The source for the wind energy systems is renewable and sustainable due to wind being caused by a combination of heating of atmosphere by the sun, earth surface irregularities and the rotation of the earth.
- Wind is cost effective due to it being free.
- Wind technology is the most competitive in terms of economics when compared to all other renewable energy technologies.
- Wind turbines can be built on the existing farms. This boosts the economy in remote areas, where the best wind sites are normally found.

Disadvantages

The disadvantages of wind energy are [29]:

- It is not a constant energy source due to the intermittent nature of wind energy.
- Wind turbines generate noise and have visual impacts.
- Threat to wildlife (e.g Birds) is a major concern.
- Possible interference with television and radio reception.
- Due to the best wind sites being mostly in remote areas which are far from where the electricity is needed, long transmission lines must be built to bring the electricity from the wind farm to the city.

2.4.5 Solar energy

2.4.5.1 Overview

Solar energy is the energy generated from the sun in the form of electric or thermal energy. It is captured in many different ways however; the most common form of capturing solar energy is with Photovoltaic (PV) solar panels that convert the sun rays into usable electricity. In addition to using PV to generate electricity, solar energy is also used in thermal applications to heat indoor spaces or fluids.

The solar panels are installed at three different scales namely residential, commercial and utility. The residential scale solar is predominantly installed on rooftops of the homes or in open lands and is generally between 5 and 20 kilowatts (kW). Commercial scale panels are installed at a greater scale than residential panels to provide businesses with on-site solar power. Lastly, utility scale solar projects are typically large and are in the range of several MW installations that provide solar power to a large number of utility customers [30]. This research is only limited to electricity production. Consequently, only PV systems will be discussed further.

2.4.5.2 Components and operation

PV energy systems consist of different components. Figure 2.7 below shows a typical grid-tied PV system.

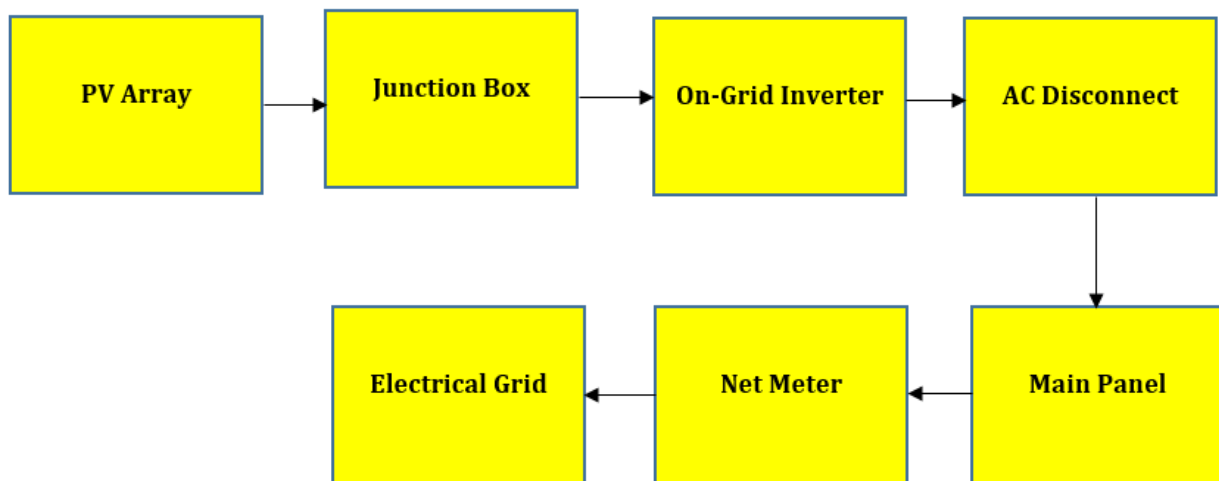


Figure 2.7: Typical grid-tied PV system [31]

The components that are involved in a PV system are as follows [31]:

- **PV modules**-consist of PV cells assembled together and are the building blocks of a PV system. Their function is to convert the energy collected from the sun into electricity.
- **Junction Box**-houses and electrically connects the PV strings.
- **On-Grid Inverter**-converts the DC power to AC power.
- **AC disconnect**-separates the DC-AC inverter from the utility's power grid.
- **Main panel**- comprises of electromechanical devices that are used to disconnect the PV system from the grid when necessary.
- **Net-meter**- used to monitor the inflow and outflow of power between PV system and the electrical grid.

A PV system's main function is to generate electricity. The system can either be grid-tied or off grid, however, the operation is the same. When the incident light energy on the PV module is enough to result in electron production, DC power is generated at the output terminal of the PV arrays. The generated DC power is then fed to the power converters which in turn perform the DC to AC conversion. The AC energy can now be used to supply loads directly or through the utility grid by means of net metering facility. If the generated power is used for local consumption at the generation level itself, then it is said to be an off-grid system while it is called grid-tied system if it is continuously fed to the utility grid [31].

2.4.5.3 Classification of PV systems

PV systems are normally classified according to their functional and operational requirements, their component configurations and the connection to other power sources and electrical loads. As stated before, PV systems can either be grid-tied or stand-alone systems and those are the two principal classifications of a PV system. Grid-tied systems are designed to operate in parallel with the utility grid as illustrated in Figure 2.7. Stand-alone systems are generally designed to operate independent of the utility grid and usually supply certain DC and some AC loads. The simplest type of a stand-alone system is a direct-coupled system, where the DC output of the PV array is connected directly to the load [32]. Figure 2.8 below shows the block diagram of a direct-coupled system.

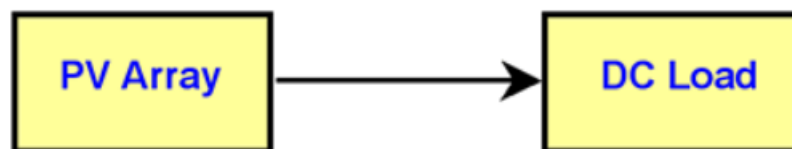


Figure 2.8: Direct-coupled system [32]

Due to the direct connection of a PV array to the load, the load can only be supplied during sunlight hours, making this type of design suitable for common applications such as water pumps, ventilation fans and water heating systems. Furthermore, batteries are used as energy storage devices for the majority of stand-alone PV systems [32]. A typical stand-alone system with batteries is shown in Figure 2.9.

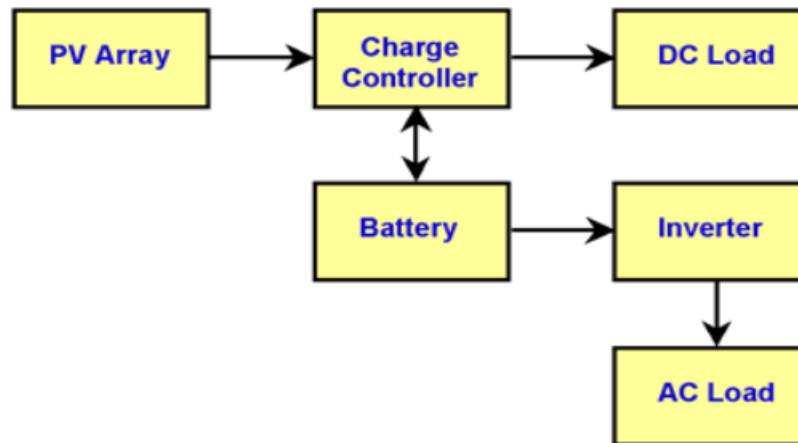


Figure 2.9: Stand-alone PV system with battery storage [32]

The battery energy storage system makes supply available to the load when the sun is not available to power the load.

2.4.5.4 Advantages and disadvantages of PV systems

Advantages

The advantages of PV systems are [33]:

- Pollution free and emit no greenhouse gases after installation.
- Reduced dependency on fossil fuels and foreign oil.
- Assistance with capital cost through Tax incentives and rebate programs.
- Flexible and versatile with respect to siting and size.
- Very minimal maintenance is required as there are no moving parts other than tracking.
- Short lead time and a high output to weight ratio.

Disadvantages

The disadvantages of PV systems are [33]:

- Very high initial cost requirements.
- Intermittent nature of solar energy. It is only available during the day when the sunlight is available.
- Cloudy days do not produce as much energy as required even during the day.
- A lot of space is required to install solar panels.
- Power production is low during winter months. This is problematic in South Africa due to system peak being experienced mostly during winter periods.

2.4.6 Benefits and challenges of DGs

2.4.6.1 Benefits

The benefits of DGs are as follows [34]-[35]:

Reduced transmission and distribution costs

Transmission and distribution costs account for approximately 30% of the electricity delivery costs on average. The lowest cost is usually achieved by the Large Power Users (LPUs) or industrial customers which take supply at medium to high voltage and the highest cost is achieved by Small Power Users (SPUs) or small customers which usually take supply from the distribution network at low voltages. The high price from transmission and distribution network is mainly due to losses and connection of the DGs on the distribution network can reduce losses which in turn reduce the transmission and distribution costs.

Rural electrification

Huge capital expenditures are generally required to connect remote areas due to the distance that is required to be covered by overhead lines to connect remote areas to the grid. However, consumption in the remote areas is usually small which makes such investments uneconomical. The effect is amplified when taking into account the transmission and distribution losses. In order to reduce the costs, DGs can be used as an alternative solution to bypass the transmission and distribution networks.

Security and reliability

DGs can provide generation diversity which reduces the dependency and risks on one generation source. In addition, DGs can also be used as back-up generators to prevent operational failures under contingency or emergency conditions.

Environmental Impact

The environmental impact of centralised generation systems is significant due to reliance on coal, fuel and to a lesser extent, the natural gas. DGs can be used to mitigate the impact on the environment.

Energy efficiency

Generally, the efficiency of a sole electricity generation hardly goes above 40%. However, combination of sole electricity generation and heat can result in an energy efficiency of up to 90% [34]. The problem is that heat and steam are even less easily transportable than electricity which justifies use of DGs through production next to the point of consumption.

Cost effective power system planning solution

In areas where high load is only for a short period of time in a year, it can be less costly to install a DG to cater for load requirements than it would be to upgrade the power delivery system to import the same amount of power.

2.4.6.2 Challenges

The challenges of DGs are as follows [35]:

Size and location

High penetration levels of DGs are still a new challenge for traditional power systems. Power injection by a DG at a distribution level changes the network power flow which in turn modifies the energy losses and the voltage profiles of the system. If proper location and DG size is not chosen correctly, increased energy losses and high voltages can be experienced on the network.

System performance

Integration of DG changes the network from a passive system to an active system and some conventional protection schemes such as overcurrent protection turn out to be unsuitable. An example includes reduced line protection sensitivity due to reverse power flow on the network. The trip might not be initiated when required as a result of forward and reverse current flow which results in the line current being smaller than the overcurrent protection threshold and causing blindness to the overcurrent protection scheme. Some of the impacts of DG connection on the existing utility network performance include [35]:

- False tripping of feeders.
- Unwanted islanding.
- Unsynchronised reclosing.
- Prevention of auto-reclosing.
- Increased or decreased fault levels with connection and disconnection of DG.

Reverse Power Flow and Voltage Profile

Radial distribution networks are generally designed for unidirectional power flow. If the generation connected on the distribution feeder exceeds the local consumption, power flow changes the direction and becomes reversed. The reverse power flow implies a reverse voltage gradient along the radial feeder. This in turn can cause violation of voltage limits and can also result in additional voltage stress to the equipment.

2.4.6.3 Summary

The benefits listed above show that there can be economical benefits that can be achieved with DGs provided that the size, location and penetration levels are properly selected at the feasibility stage. However, system performance issues and grid code violation issues can also be experienced if the sizing and location of the DG is not properly considered. The DGs in South Africa are either customer or DoE driven and can therefore be anywhere on the network. The network operator (Eskom) does not have an influence on the location, size and penetration levels. The network operator is however required to conduct grid connection studies based on the size and location of the DG (chosen by the developer) and propose strengthening solutions to accommodate the full generation if the existing infrastructure is inadequate. The combination of intermittent nature of wind and solar resources and inability of the network operator to influence the location, availability and size of DGs has resulted in SA's power distribution system expansion being planned without considering DGs to guarantee high network strength. This approach can however result in network over-design and unnecessary capital expenditure and this report aims to investigate SA power system grid planning with distributed generation.

2.4.7 Impact of DGs on Power system planning

Yalin [1] investigated the impact of DGs on the electricity distribution network planning using new proposed network planning models for LV (≤ 1 kV) and MV (~ 20 kV) networks. The study concluded that DG integration on the network can reduce the system losses, improve voltage regulation and enhance system reliability. However, the study found that the voltage regulation can be a problem in remote areas. The study further cautioned against the uncertainties such the wrong DG location and technology type and recommended DNO to encourage DG connections in areas favoured by the existing network. This can be done by publishing the relevant information to the developers and setting different connection prices for different connection points.

Impact of DGs on power system planning, particularly on investment deferral has been studied by other researchers. Ronaldo [2] evaluated whether PV systems connected on the distribution networks postpone the strengthening detected by the distribution network expansion planning. The study network consisted of residential and commercial customers and 73 Medium Voltage (MV)/Low Voltage (LV) transformers. A typical load profile for weekdays and weekends was assumed for each customer type and the peaks of the load profiles were adjusted to 85% of the transformer nominal power. Results showed that the planning methodology that focuses only on the highest loading days which occur when the consumer demands are predominantly at maximum is no longer sufficient with introduction of PVDGs. PVDGs can change the day as well as the time of the peak. This change is only expected if the peak demand for the network is during the daytime when the sun is available. In addition, the study further concluded that a penetration level of PVDGs that changes the traditional

planning approach needs to be well understood by the relevant planning engineers and will be unique for each network. However, the study assumed that all consumers will install PVDG to assess the impact which is totally unrealistic.

Mohamed [3] also looked at the impact that dispersed generation has on the distribution network planning expansion. Network consisting of 132/33 kV 1 x 40 MVA substation supplying eight load centres through 33 /11 kV distribution transformers was used to estimate the optimal DG in terms of size and location. Results showed that DGs minimize the total planning costs (investment, operation and maintenance costs) by approximately 20% on the study network, improve voltage profiles and reduce network technical losses. The 20% reduction is derived on the basis that the network operator will influence the location, the penetration level and size of the DG. Nelson [4] also investigated whether transmission expansion planning considering DGs can defer or avoid additional new transmission infrastructure. The study used Garver 6-bus and IEEE 24-bus systems to assess the impact and the DG was modelled as the aggregation of small DGs at the distribution bus. The study concluded that the DG can be an alternative to capital investment prioritisation in the transmission system infrastructure.

Antonio and Pierluigi [5] evaluated the impact of network investment deferral on DG expansion. The evaluation was conducted on an 83-bus 11.4 kV radial distribution system fed by 33/11.4 kV 2 x 20 MVA substation. To assess the benefits brought about by the DGs, seven potential DG locations were defined and DGs were assumed to be connected at the start of the planning horizon with a constant power factor of 0.9. Results showed that the benefits such as reduced distribution network costs and improved overall energy efficiency can be realised, provided that the Distribution Network Operator (DNO) can influence the location and operation of the DG. In addition, the study further revealed the need for a proper legislation to potentially oblige network operators to require power generation as an alternative to distribution network strengthening.

Furthermore, Phillipe and Joao [6] evaluated transmission system planning considering solar distributed generation penetration. IEEE 24 bus system was used for the analysis and the study assumed penetration levels of 0%, 10%, 15% and 20% of the annual peak demand connected at each bus. In addition, the load was deliberately increased so that the system can be constrained. Results showed that penetration of solar distributed power generation can provide a better and safe operation of the system while reducing transmission losses, greenhouse gas emissions and operation costs, provided that the peak demand coincides with the solar power generation. Jun, John, Zhao and Kit [7] looked at flexible transmission network planning considering the impact of DGs using the IEEE 14 bus system and considered both the Concentrated Solar Power (CSP) and Wind power. Results showed that transmission investment deferral can be realised with the introduction of DGs. However, a high penetration level of DGs reduces its effect on transmission investment deferral due to further strengthening that is required to connect the DGs to the network.

Yan, Chenghong and Furong [8] evaluated investment deferral resulting from microgeneration (PV, wind, solar water heating, etc.) for Extra High Voltage (EHV) distribution networks. The evaluation was conducted on a 33 kV network for the city of Bath considering different scenarios (even distribution, distribution according to load buses, etc.). The study assumed a certain penetration level of microgeneration and the results showed that the loading requirements for the 33 kV network from the upstream network decreases due to microgeneration. In addition, the study also found out that connecting microgeneration at different locations brings different benefits. Consequently, an optimal allocation and concentration level is of utmost important. Wang, Ochoa, Harrison, Dent and Wallace [9] evaluated the investment deferral when DGs are incorporated in the distribution network planning. The evaluation was conducted on a 20 bus distribution system using non-intermittent DGs (i.e CHP, CCGT) which were placed on each node with assumed penetration level and load growth for a pre-defined period. The strengthening required due to DGs was not considered due to a relatively small DG penetration level considered in the study. Results showed that the investment deferral varies depending on the location, size and control strategy of the generator.

Moreover, [10] studied the impact of DGs on distribution investment deferral using different technologies (CHP, PV and Wind). A profile for the CHP was based on the recorded real annual data while the profiles for PV and Wind were theoretical values deduced using the relevant methods. Results showed that DGs could defer network investment in the face of expected natural load growths. In addition, PV and CHP plants showed more positive impact than wind energy due to highest randomness of wind energy production. Distribution planning and operation with intermittent power production has also been studied by Fred and David [36]. Results revealed that PV systems generated about 50% of their rated output during system peak compared to wind turbine systems which only generated 8%. The study further revealed that the impact on the planning process is dependent on the penetration level of the intermittent generation.

2.5 Conclusion

This chapter reviewed the impact of distributed generation on power system planning. The review revealed both benefits and challenges that are expected as a result of DG integration onto the network. The most notable benefit is the reduced power flow from the upstream network due to the connection of DG at distribution level. The reduced power flow from the upstream network impacts the traditional network planning approach which could further impact capital investment decision making at transmission and distribution levels. As such, distributed generation impact on the transmission and distribution grid planning has been studied by other researchers as stated above.

It is evident from the literature that benefits such as reduction in power losses, voltage regulation improvement and capital investment deferrals can be realized with introduction of DGs to the system, provided that the correct location, size and penetration level is selected. Additionally, it is also evident

from the literature that DGs were strategically placed on the study networks, thereby assuming a regulated market where the DNO is able to influence the location, size and penetration levels. This is currently not the case in SA as DGs which are predominantly wind and solar are either customer driven or DoE driven and as a result, they can be anywhere on the network. Previous studies have not yet tested a scenario where the market is unregulated.

Furthermore, previous studies also strategically increased the DG sizes on different nodes to deduce the potential benefits, thereby assuming a certain level of generation availability during the network peaking period. Due to the intermittent nature of wind and solar energy resources, availability of distributed generation deduced theoretically is not always guaranteed in reality. However, none of the studies have yet tested the benefits of DGs using real measured data to confirm whether the capital investment deferrals and other technical benefits can indeed be achieved in reality.

3 METHODOLOGY

3.1 Software selection

The simulation tool that will be used in this research is DIgSILENT PowerFactory simulation tool due to its robustness and reliability. The tool is the leading power system analysis software for generation, transmission and distribution systems. It covers a wide range of functionalities from standard features to highly sophisticated and advanced applications including but not limited to integration of DGs and load flow studies for power system planning and operation. The tool offers a wide range of load flow calculation methods including AC Newton Raphson technique and linear DC technique [37]-[38].

For the purpose of the research, the tool will be used to provide load flow results using Newton Raphson method. Newton Raphson has been chosen due to it being the most widely used technique for root finding. It is an iterative technique used to solve a set of nonlinear algebraic equations. In comparison to Gauss Seidal method, it provides a fast response and convergence and is defined by the following power flow equations [39]-[40]:

$$P_i = V_i \sum_{j=1}^m (V_j * Y_{ij} * \cos(\phi_{ij} + \delta_j - \delta_i)) \dots \dots \dots (3.1)$$

$$Q_i = V_i \sum_{j=1}^m (V_j * Y_{ij} * \sin(\phi_{ij} + \delta_j - \delta_i)) \dots \dots \dots (3.2)$$

where;

V_i =Voltage at i^{th} bus

V_j =Voltage at j^{th} bus

Y_{ij} = admittance of i^{th} and j^{th} bus

ϕ_{ij} =admittance angle at node i and j

δ_i = angle of i^{th} bus

δ_j = angle of j^{th} bus

3.2 Assumptions

For the purpose of simulations, the following will be assumed:

- Literature revealed that impact of DG integration on capital investment is largely influenced by reduced demand from the upstream network, reduction in transmission line losses and voltage regulation. Consequently, only thermal rating, technical losses and voltage limit parameters will be assessed in the research.

- The technical criteria that will be applied to the power system simulation studies contained in this research will be based on the South African grid code version 8[41] since a section of SA network will be used for simulations.
- The technical criteria that will be used are shown in Table 3.1.

Table 3.1: Technical criteria[41]

Description	Limit
Voltage regulation	95-105%
Thermal rating	100% since only normal operating conditions will be considered
Losses	subjective

There is no limit prescribed for losses. The onus is on the responsible planning engineer to conduct a technical benefit to cost analysis when assessing losses on the network development planning process.

- For the existing DGs on the network, the selected control mode as set in the field will be used. For future or new plants, a unity power factor control mode will be used as per [42] since the control mode of these plants is not known yet.
- 2019 real measured data with a sampling time of 60 minutes will be utilised as a base year data. 2020 data has not been selected as a base year data due to it being unreliable as a result of missing data and Covid which ramped down operations in the area during the time when some of the substations in the area are expected to be peaking.
- Both high and low load conditions will be studied so that the extreme ends of the network can be adequately analysed.

3.3 Study network

A South African network consisting of renewable energy plants will be used due to easy access to the network parameters. Only the relevant network required for the study will be shown in the report. Though the network will be built as it is in the field, the actual substation names will not be used due to sensitivity of the data to be used for simulations. Dummy names for the substations will therefore be used to protect the sensitivity of the data. The network that will be used to conduct simulations in the report is shown in Figure 3.10.

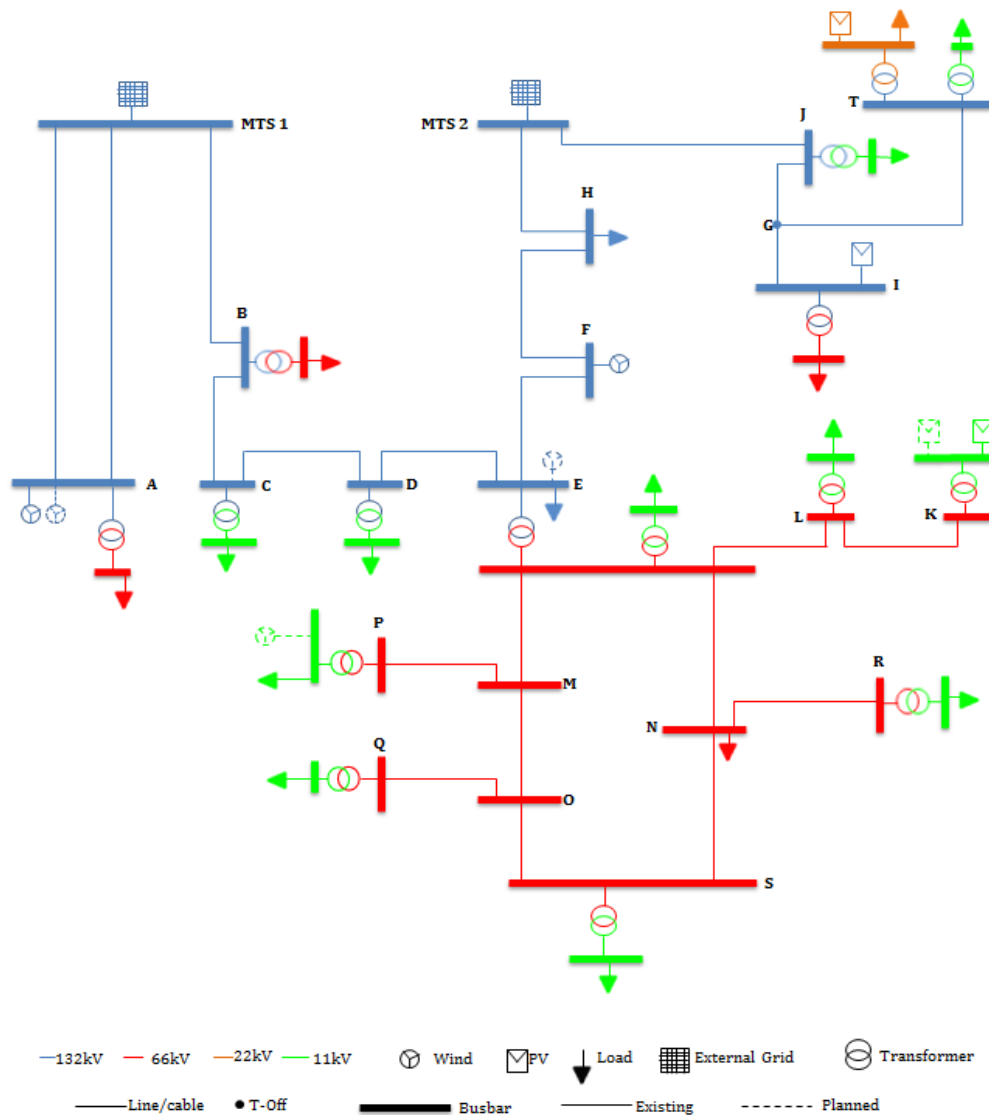


Figure 3.10: Study network

The study network is a 21 bus network comprising of 11, 22, 66 and 132 kV. The diversified load demand peak in the area was 346 MVA (321 MW, 149 MVAR) on the 6th February 2019 at 16:00 and the study area has a summer peak. The study network comprises of 3 branches and these branches peaked as follows:

- MTS1 to A branch-177 MVA on the 6th February 2019 at 16:00. This branch peaked at the same time as area peak.
- MTS1 to MTS2 branch-176 MVA on the 7th February 2019 at 15:00. This branch experienced a loading of 172 MVA during area peak. This is equivalent to 97% of its maximum load.
- MTS2 to J branch-63 MVA on the 7th March 2019 at 12:00. This branch experienced a loading of 57 MVA during area peak. This is equivalent to 90% of its maximum load.

Furthermore, the study network comprises of installed DGs of 296 MW (207 MW Wind and 89 MW PV) with expected future DGs of 589 MW (495 MW Wind and 94 MW PV) within the study period. This

generation is predominantly connected on the 132 kV network and thus only affecting mostly line loading. In addition, Table 3.1 shows that none of the substations are expected to be loaded beyond 100% of the installed capacity. Consequently, only line loading results will be shown in the report. The parameters for the study network are presented in Table 3.2 and Table 3.3.

Table 3.2: Substation Parameters

Station Name	Transformation	Installed Capacity(MVA)	Loading (MVA)		Generation (MW)	
			2019	2029	2019	2029
A	132/66 kV	320	177.1	214.0	140.0	280.0
B	132/66 kV	80	20.6	22.5	0	0
C	132/11 kV	40	26.4	29.9	0	0
D	132/11 kV	20	4.5	8.6	0	0
E	132/66 kV	160	68.0	72.0	0	140.0
	132/132 kV	-	60.0	60.0	0	0
F	132/132kV	-	-	-	65.4	65.4
H	132/132 kV	-	1.6	15.0	0	0
I	132/66 kV	160	56.9	70.3	75.0	75.0
J	132/11 kV	10	3.7	4.3	0	0
K	66/11 kV	10	0	0	5.0	10.0
L	66/11 kV	10	3.3	4.2	0	0
M	66/66 kV	-	0	0	0	0
N	66/66 kV	-	0	0	0	0
O	66/66 kV	-	0	0	0	0
P	66/11 kV	10	1.4	1.8	0	8.4
Q	66/11 kV	10	7.1	11.0	0	0
R	66/11 kV	20	6.9	8.7	0	0
S	66/11 kV	60	27.9	35.6	0	0
T	66/11 kV	10	3.0	3.0	0	0
	66/22 kV	10	2.6	5.0	9.5	9.5

Table 3.3: line Parameters

Line Name		Voltage level (kV)	Conductor Type	Length(km)	Templating Temperature	Thermal Capacity (MVA)
From	To					
MTS1	A	132	3 x Bear	24/conductor	50	119/conductor
MTS1	B	132	Bear	15	50	119
B	C	132	Bear	24	50	119
C	D	132	Bear	6	50	119
D	E	132	Bear	33	50	119
F	E	132	Bear	29	50	119
H	F	132	Bear	25	50	119
MTS2	H	132	Bear	11	50	119
MTS2	J	132	Bear	43	50	119
J	G	132	Bear	18	50	119
G	I	132	Bear	24	50	119
G	T	132	Chickadee	15	70	128
E	M	66	Hare	13	50	33
M	P	66	Hare	5	50	33
M	O	66	Hare	15	50	33
O	Q	66	Hare	8	50	33
O	S	66	Hare	1	50	33
E	N	66	Hare	24	50	33
N	R	66	Hare	23	50	33
N	S	66	Hare	13	50	33
E	L	66	Chickadee	28	70	128
L	K	66	Chickadee	12	70	128

3.4 Renewable energy forecasting

Future studies will require estimation of renewable generation availability. In order to estimate the availability of renewable generation during the network peaking period for future studies, renewable

energy forecasting is necessary. This data is currently not available because the network operator does not include DGs as part of the network development planning. Renewable energy forecasting has been thoroughly investigated by other researchers. Consequently, different forecasting methods will not form part of this research. However, literature revealed that time series method is the most widely used method for wind and solar energy forecasting [42]-[45].

Wind and solar energy forecasting require forecasting of meteorological data such as solar radiation and wind speed. This data is plugged into the technology models to estimate the expected power output of the plant. Simplified widely used solar and wind energy models are shown below.

Solar Model

Relationship between output power of the PV panels and the irradiation data is described by the following equation [45].

$$P_{pv} = I \times A_{pv} \times \eta_{pv} \dots \dots \dots (3.3)$$

where;

I is the hourly solar irradiance in kW/m²

A_{pv} is the area of the PV panels in m²

η_{pv} is the efficiency of the PV panels

Wind Model

The wind energy model that has been adapted by many researchers is illustrated by the following equation [45].

$$P_w = \begin{cases} 0 & \text{if } V(t) \leq V_{ci} \text{ or } V(t) \geq V_{co} \\ P_r \frac{V(t)-V_{ci}}{V_r-V_{ci}} & \text{if } V_{ci} < V(t) < V_r \\ P_r & \text{if } V_r < V(t) < V_{co} \end{cases} \dots \dots \dots (3.4)$$

where;

$V(t)$ is the wind speed at any time t in m/s

V_{ci} is the cut-in wind speed (when the turbine starts generating power)

V_r is the rated wind speed (maximum wind speed)

V_{co} is the cut-out wind speed (when the turbine stops generating power).

P_r is the output power of the wind turbine

Solar radiation and wind speed forecast are currently not available for the 10 year study period. However, historical renewable generation data is available and will be used to estimate the availability of renewable generation plants during the future network peaking period. This is defined as

Availability Factor (AF) of the renewable power plant. Due to forecasting not being the focal point of this research, the renewable generation plant availability factor for future studies will simply be taken as a mean (average approach method) of calculated individual AFs using historical data. The average approach method calculates the future values using past data, thus assuming that the future value will more or less resemble the past. In mathematical terms;

$$AF_{ave} = \frac{AF_1 + AF_2 + \dots + AF_n}{n} \dots \dots \dots (3.5)$$

where;

AF_{ave} is the average value

$AF_1 + AF_2 + \dots + AF_n$ are individual factors for each year

n-number of years

$$AF = \frac{P_{out}}{P_{max}} \dots \dots \dots (3.6)$$

Where,

P_{out} is the actual power output of the plant during network peak

P_{max} is the maximum output of the plant.

3.5 Simulation Protocol

The study network comprises of three different branches which peak at different times. Consequently, each branch will be studied separately. In order to assess the impact of DGs on the South Africa's power system planning, the following procedure will be followed:

- Conduct 2019 steady state load flow studies under normal operating conditions during high and low load periods using historical load data without distributed generation plants and document the results.
- Use the detailed load forecast that has been compiled by the network operator to conduct 2029 steady state load flow studies under normal operating conditions during high and low load periods without distributed generation plants and document the results.
- Conduct 2019 steady state load flow studies under normal operating conditions during high and low load periods using historical load data with distributed generation plants and document the results.
- Perform a high level distributed generation forecast using the methodology as described in section 3.4 of the report. Forecast results are shown in the appendix section.

- Use results from the distributed generation forecast to conduct 2029 steady state load flow studies under normal operating conditions during high and low load periods using historical load data with distributed generation plants and document the results.
- Compare the results without distributed generation with the results that incorporate distributed generation.

4 SIMULATION, DATA ANALYSIS, RESULTS AND DISCUSSION

4.1 Load flow studies without distributed generation

4.1.1 Analysis of 2019 loading and voltage levels without DGs

The load flow results for both high and low load conditions using real measured data are presented below for different branches.

MTS1-A branch

The results for the MTS1-A branch are shown in Figures 4.1 and 4.2 below.

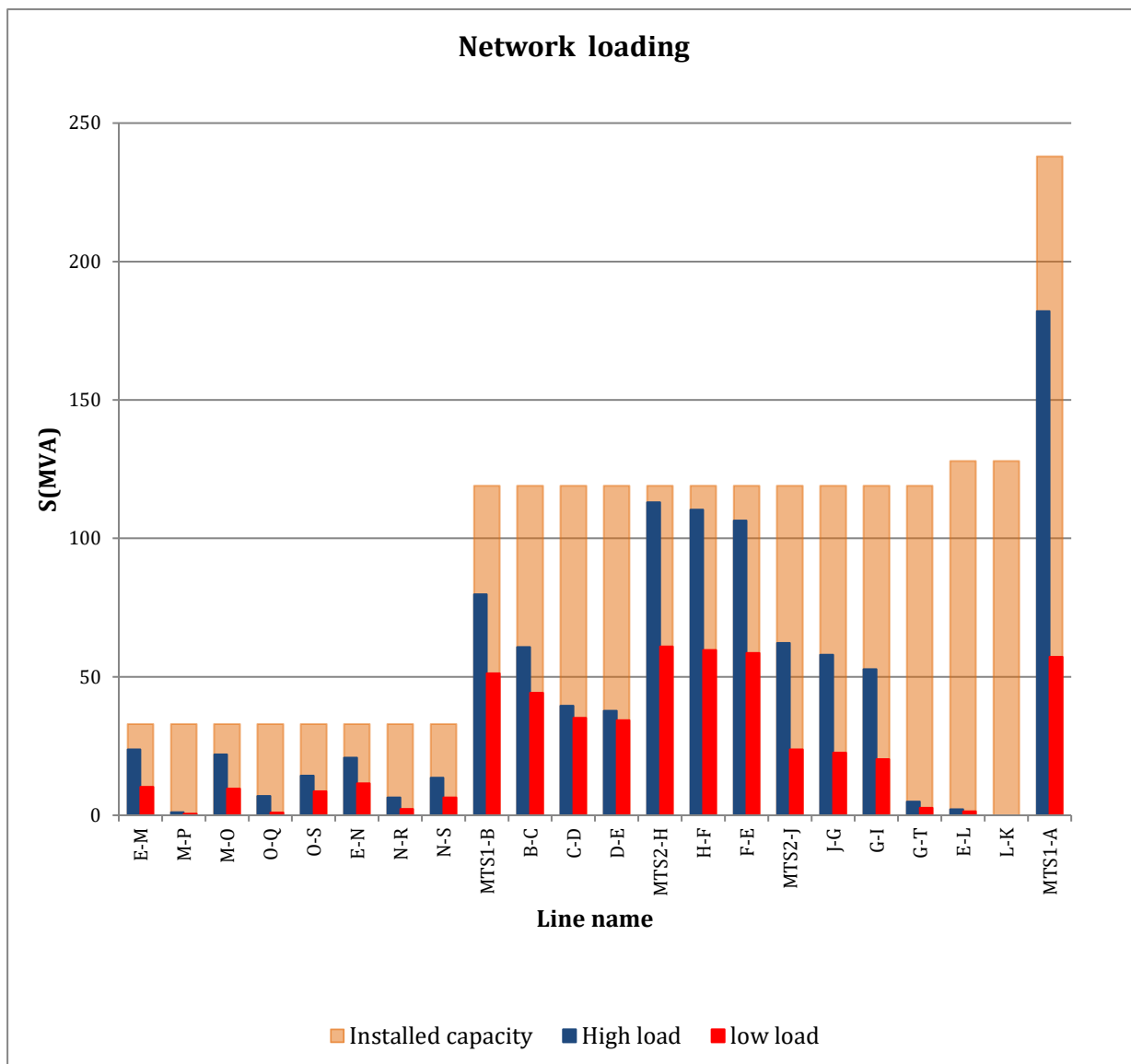


Figure 4.1: MTS1-A 2019 loading and installed capacities without DGs

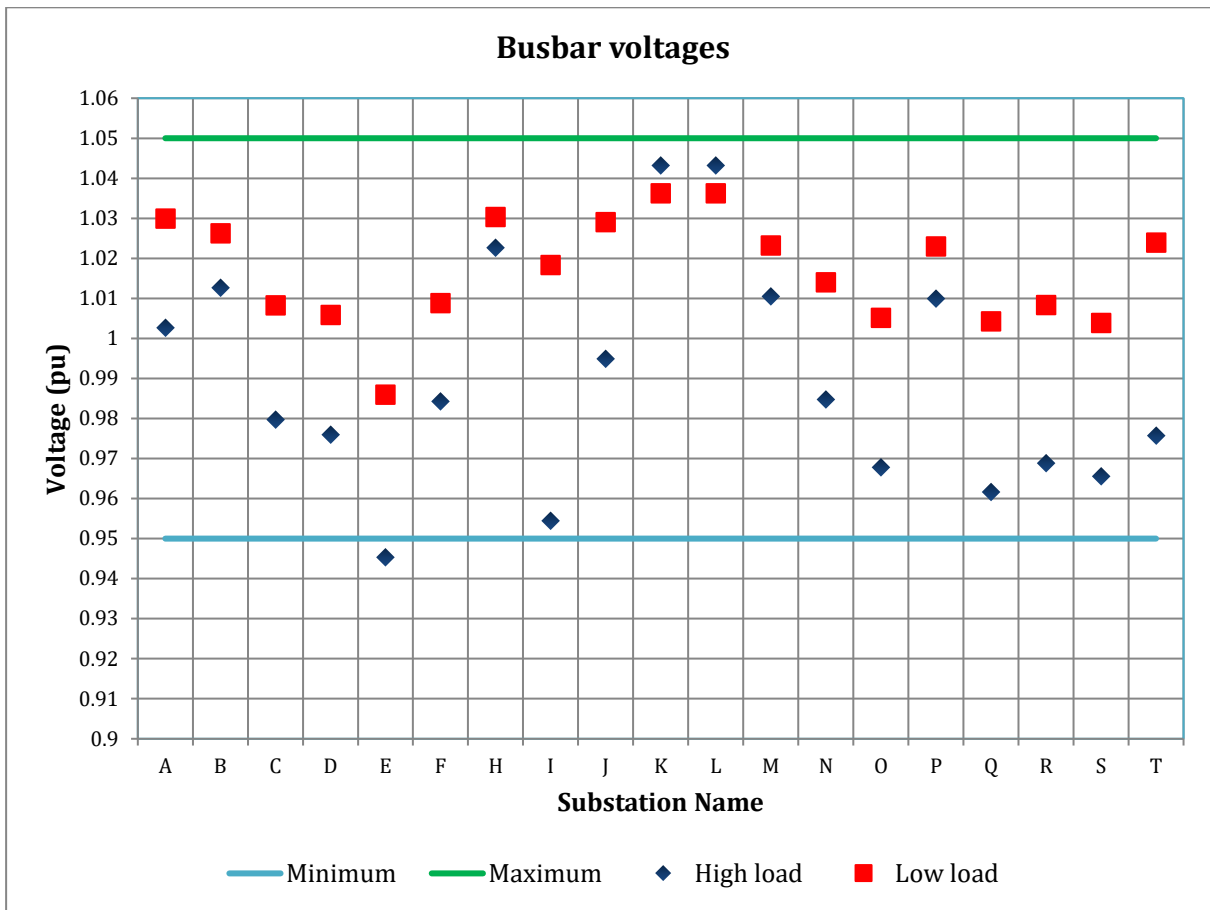


Figure 4.2: MTS1-A 2019 voltage levels without DGs

No thermal constraints were experienced in 2019 on the network during low and high load conditions of the MTS1-A branch. No voltage constraints were experienced during low load conditions. However, low voltages were experienced at substation E during high load conditions. As per the grid code, the minimum voltage limit on the network is 0.9500 pu but substation E experienced a minimum voltage of 0.9453 pu. Substation E is located at 78 km away from MTS1 and 65 km away from MTS2. MTS1 and MTS2 are the nearest substations to substation E with 132 kV voltage controlled busbars. As stated before, the supply from MTS1 to E and MTS2 to E is via 132 kV Bear lines. Every conductor has specific impedance (resistance and reactance) per km which is dependent on the design and construction of the conductor.

Due to the impedance of the 132 kV Bear line and current flowing on the network, voltage drop was experienced as a result of voltage being calculated as $V=I*Z$ where I is the current flowing through the line. The voltage drop along the 132 kV line resulted in substations on the receiving end experiencing voltage that is less than the sending end voltage. The relationship between sending end voltage, voltage drop and receiving end voltage is described by the following equation:

$$V_r = V_s - V_d \dots \dots \dots (4.1)$$

where;

V_r is the receiving end voltage

V_s is the sending end voltage

V_d is the voltage drop on the network.

Due to network characteristics which include but not limited to location of the load point relative to the nearest controlled busbar and size of the load, voltage drop along the network resulted in substation E experiencing voltage that is below the prescribed limit in the SA grid code. The network grid losses obtained from the simulations under high and low load conditions were 14.36 MW and 4.19 MW respectively.

MTS1-MTS2 branch

The results for the MTS1-MTS2 branch are shown in Figures 4.3 and 4.4 below.

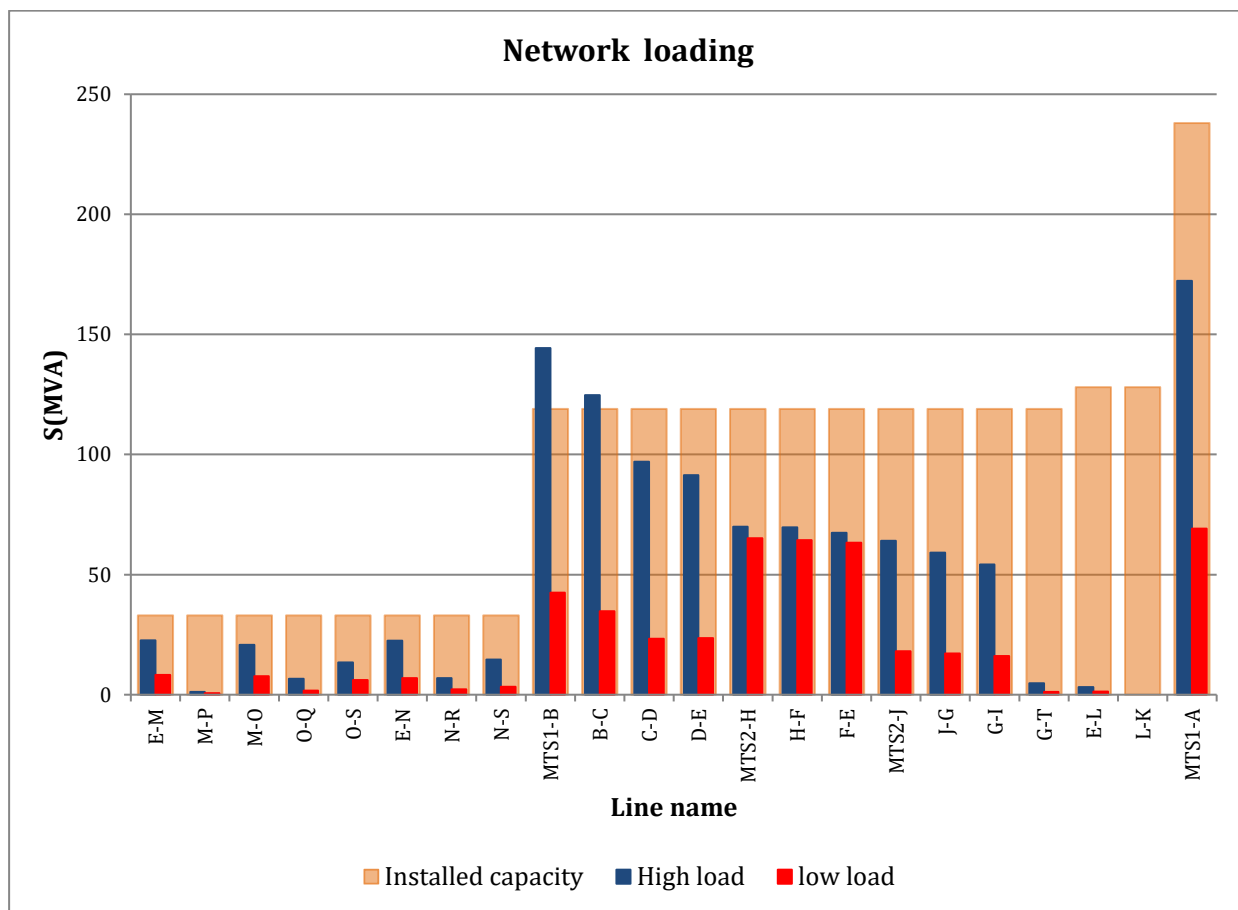


Figure 4.3: MTS1-MTS2 2019 loading and installed capacities without DGs

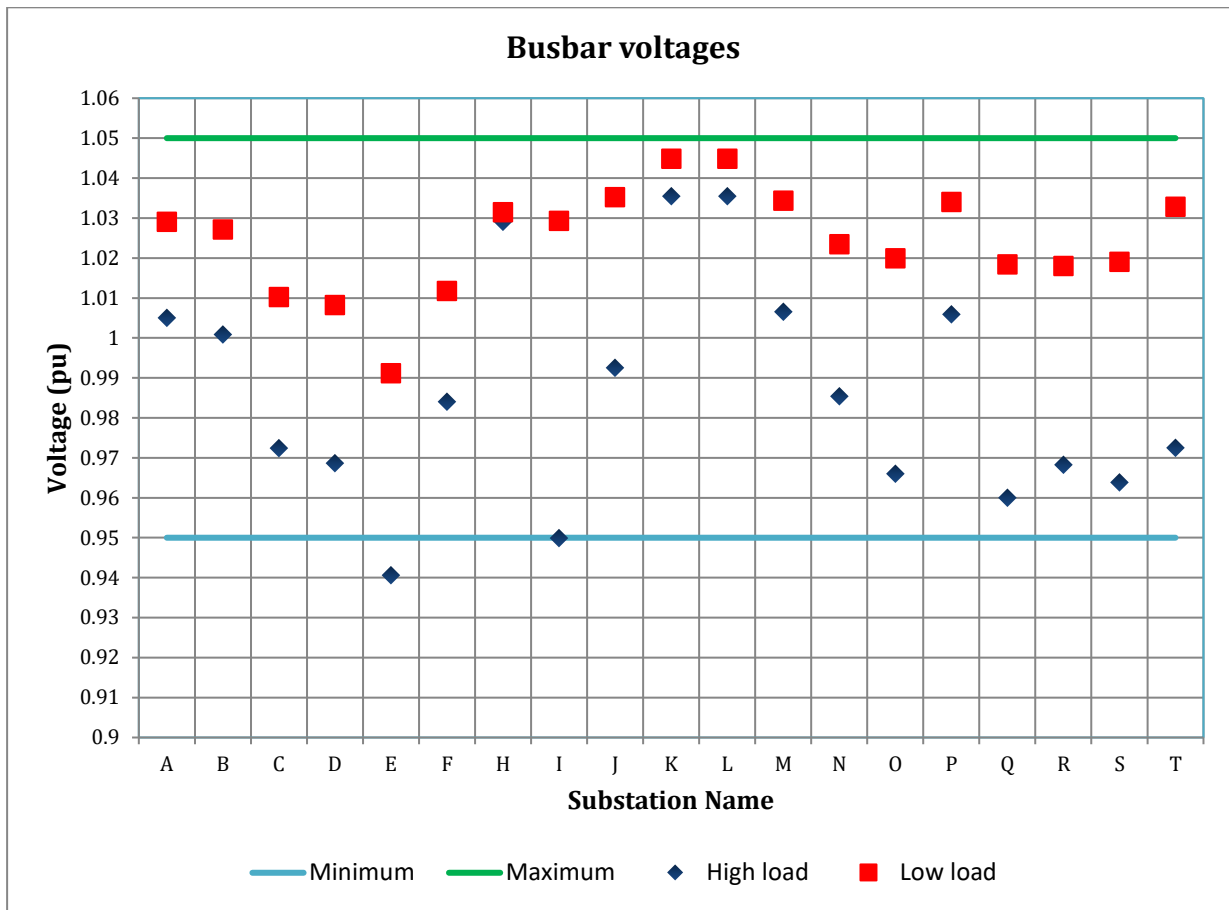


Figure 4.4: MTS1-MTS2 voltage levels without DGs

No thermal constraints were experienced in 2019 on the network during low conditions. However; thermal constraints were experienced during high load conditions on the MTS1-B and B-C line sections. These sections are rated for 119.20 MVA under normal operating conditions and the loading were 144.34 MVA and 124.75 MVA respectively. This is equivalent to 121% and 105% of MTS1-B and B-C thermal rating respectively. These sections which are close to the electrical source supplying the load and carry the whole load for the branch, experienced overloading because the total load of the branch exceeded their ratings. Due to power consumption by different loads from different substation, the loading on the lines reduces with the distance away from the electrical source. This is the reason B-C branch overloading was only 5% while MTS1-B overloading was at 21%.

Furthermore, low voltages were experienced at substations E and I during high load conditions. As per the grid code, the minimum voltage limit on the network is 0.9500 pu but substation E and I experienced minimum voltages of 0.9406 pu and 0.9499 pu respectively. The reasons that have been stated above still hold. The network grid losses obtained from the simulations under high and low load conditions were 16.70 MW and 3.76 MW respectively.

MTS2-J branch

The results for the MTS2-J branch are shown in Figures 4.5 and 4.6 below.

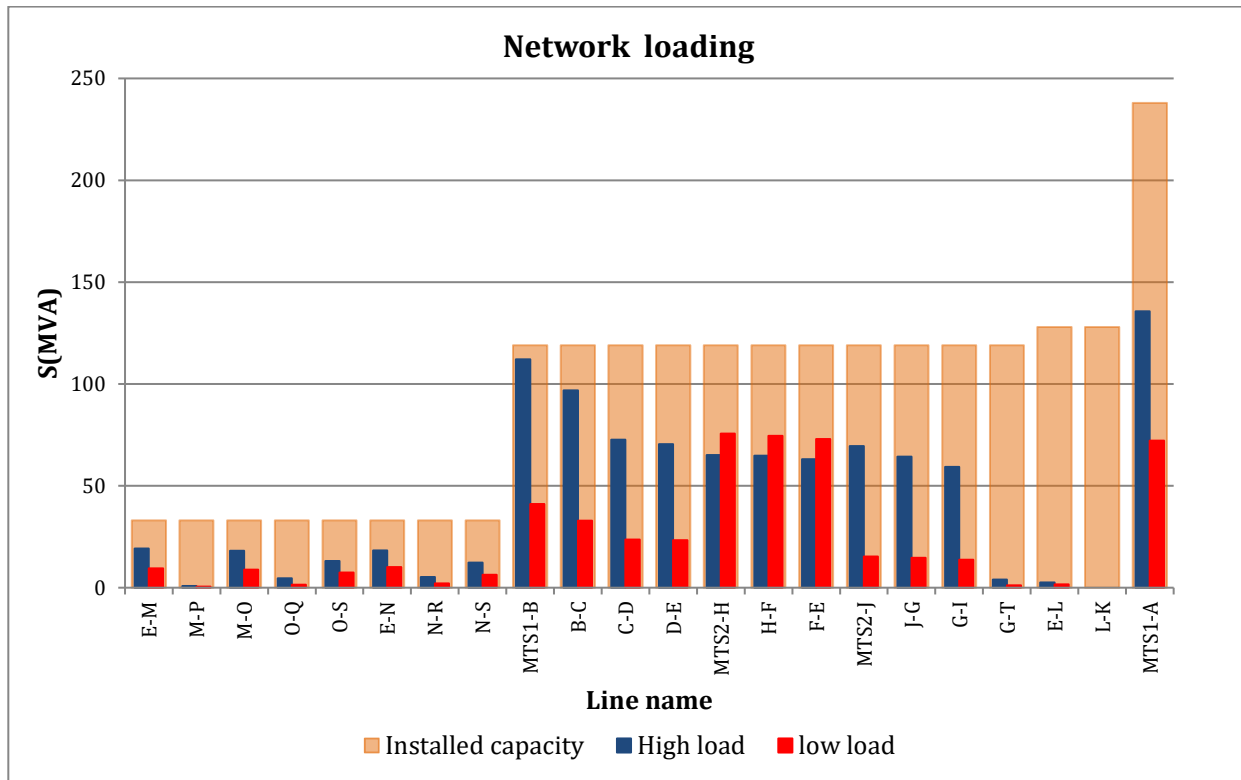


Figure 4.5: MTS2-J 2019 loading and installed capacities without DGs

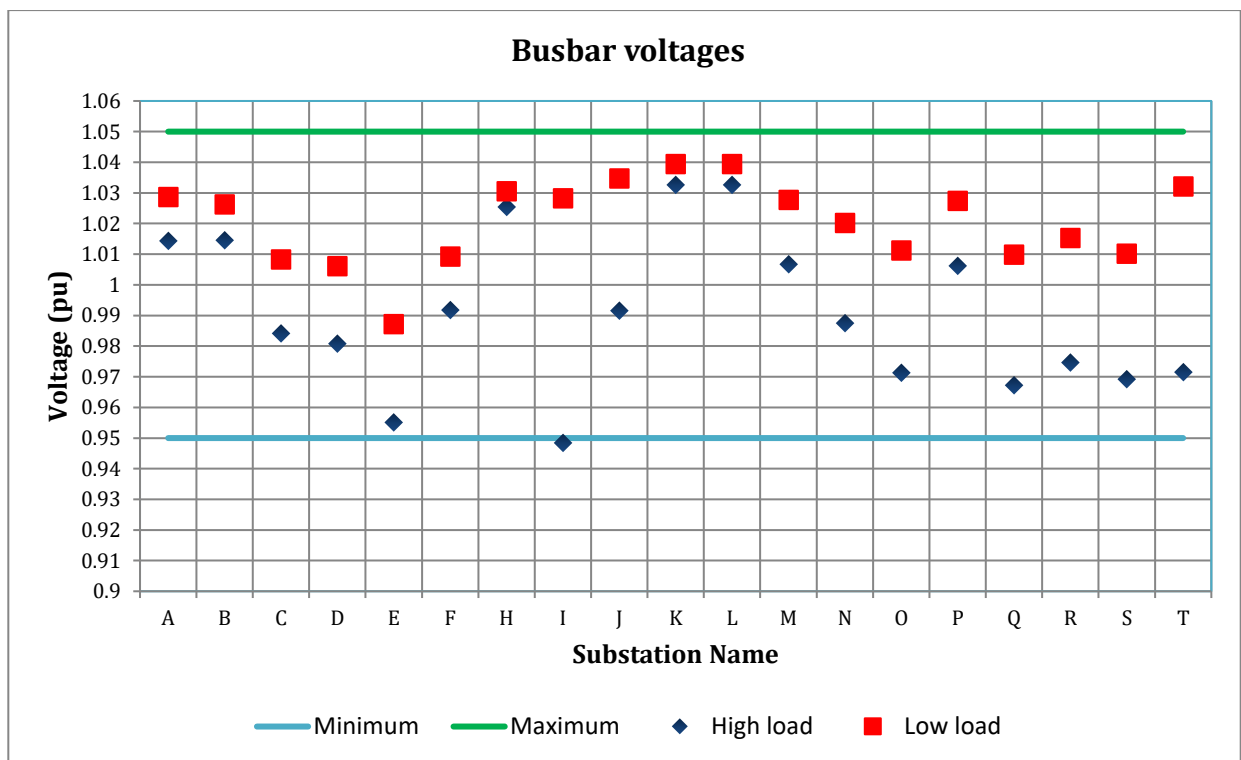


Figure 4.6: MTS2-J 2019 voltage levels without DGs

No thermal constraints were experienced in 2019 on the network during low and high load conditions of the MTS1-J branch. However, low voltages were experienced at substation I during high load conditions. As per the grid code, the minimum voltage limit on the network is 0.9500 pu but substation I experienced a minimum voltage of 0.9484 pu. The reasons that have been stated above still hold. The network grid losses obtained from the simulations under high and low load conditions were 12.30 MW and 4.45 MW respectively.

4.1.2 Analysis of 2029 loading and voltage levels without DGs

MTS1-A branch

The loading results for the MTS1-A branch are shown in Figure 4.7 below.

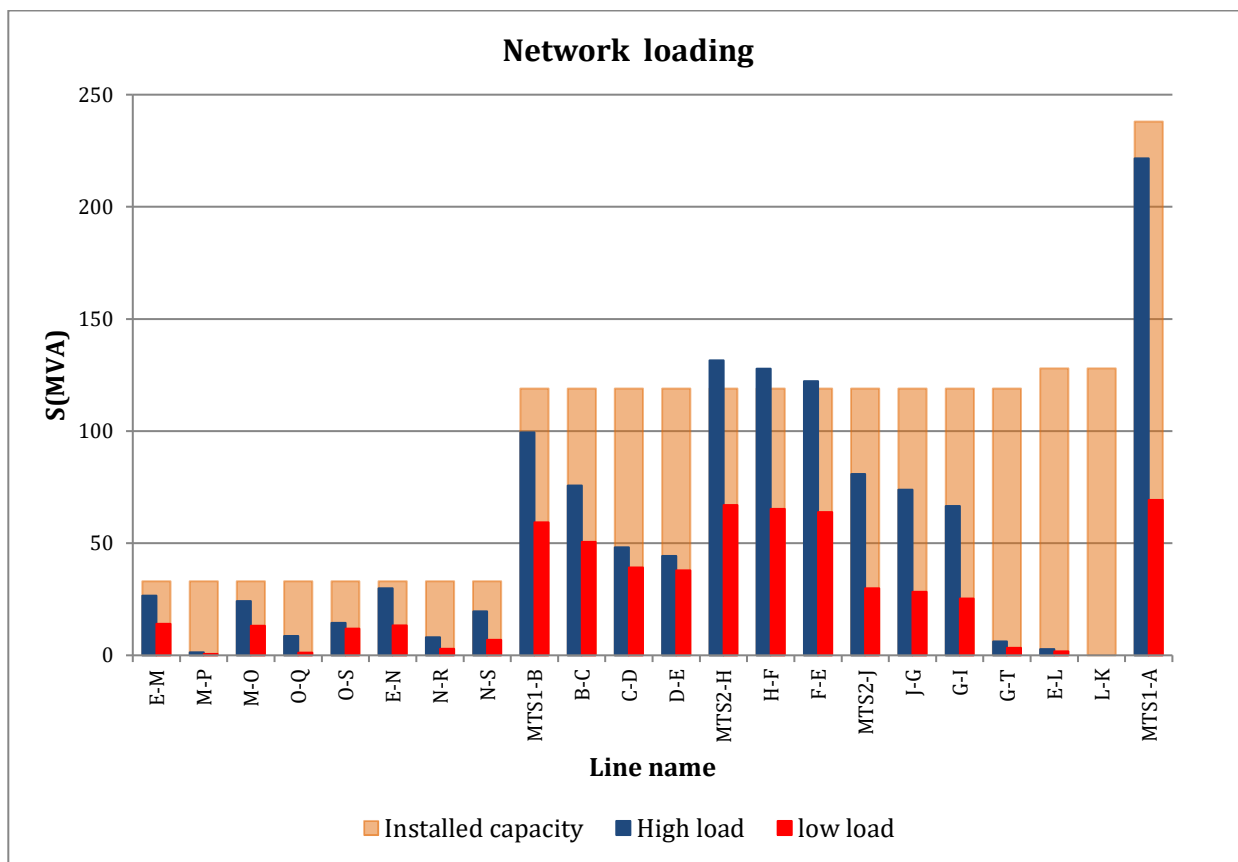


Figure 4.7: MTS1-A 2029 loading and installed capacities without DGs

Thermal issues are anticipated on MTS2-H, H-F and F-E line sections under high load conditions. These sections are rated for 119.20 MVA and the simulated load on the line is expected to be 131.56 MVA, 127.83 MVA and 122.24 MVA respectively. The voltage results for the MTS1-A branch are shown in Figure 4.8 below.

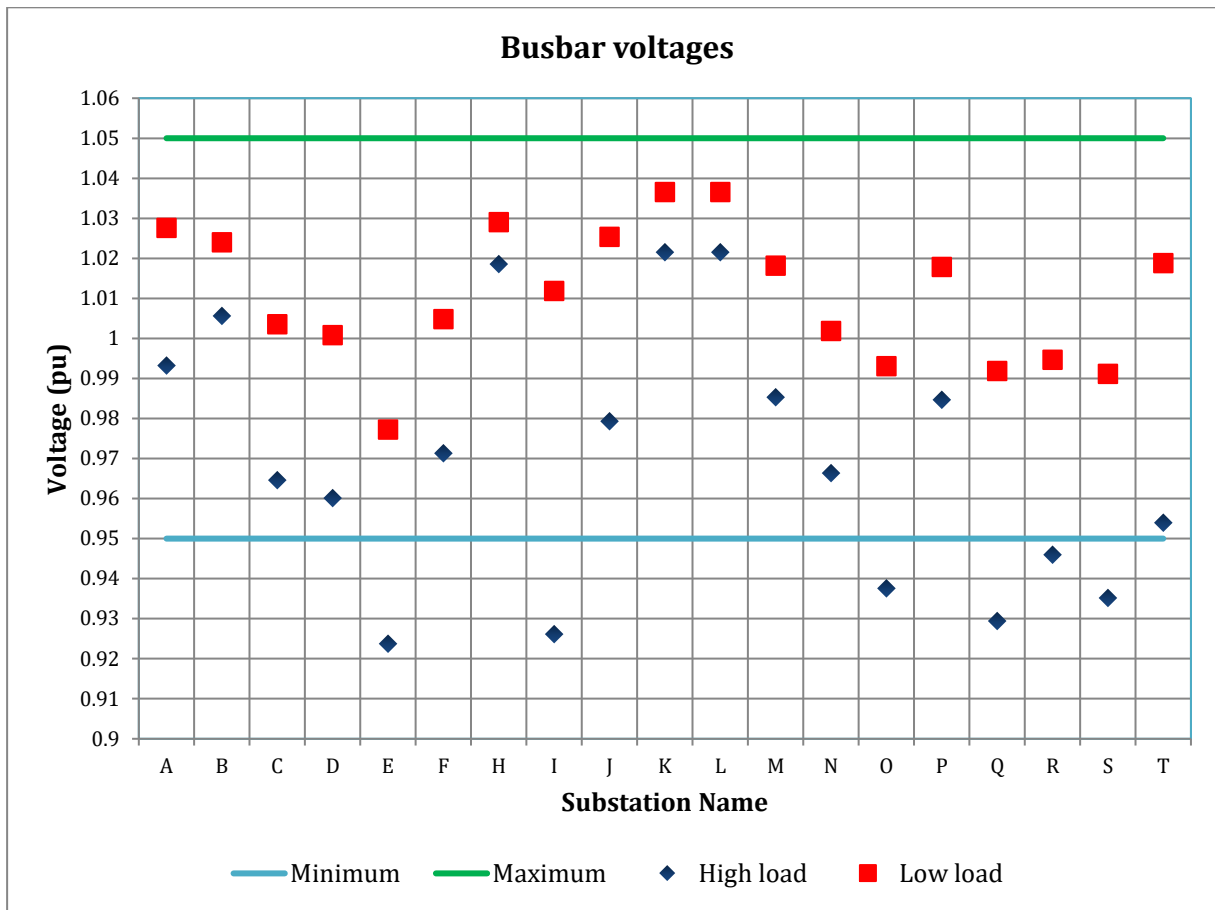


Figure 4.8: MTS1-A 2029 voltage levels without DGs

Low voltages are also expected at substation E, I, O, Q, R and S. The anticipated voltages at these substations are 0.9237 pu, 0.9261 pu, 0.9375 pu, 0.9294 pu, 0.9459 pu and 0.9351 pu. These voltages are below the 0.9500 pu limit as per the grid code. The reasons that have been stated above still hold. The expected network grid losses under high and low load conditions are 20.85 MW and 5.08 MW respectively.

MTS1-MTS2 branch

The results for the MTS1-MTS2 branch are shown in Figures 4.9 and 4.10 below. Thermal issues are anticipated on MTS2-B and B-C line sections under high load conditions. These sections are rated for 119.20 MVA but the simulated load on the line is expected to be 164.15 MVA and 139.49 MVA respectively. Low voltages are also expected at substations E, I, O, Q, R, S and T. The anticipated voltages at these substations are 0.9177 pu, 0.9198 pu, 0.9249 pu, 0.9170 pu, 0.9317 pu, 0.9224 pu and 0.9494 pu. These voltages are below the 0.9500 pu limit as per the grid code. The reasons that have been stated above still hold. The expected network grid losses under high and low load conditions are 23.42 MW and 4.37 MW respectively.

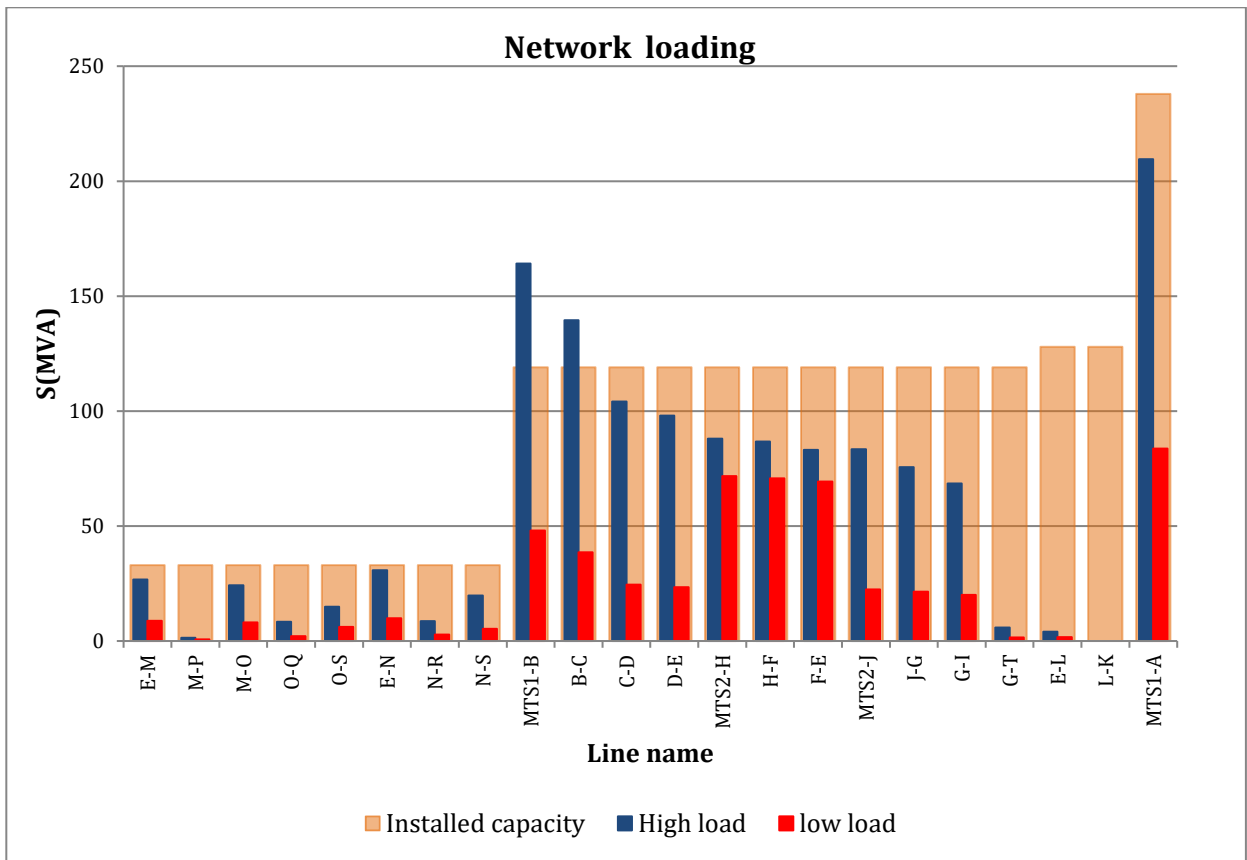


Figure 4.9: MTS1-MTS2 2029 loading and installed capacities without DGs

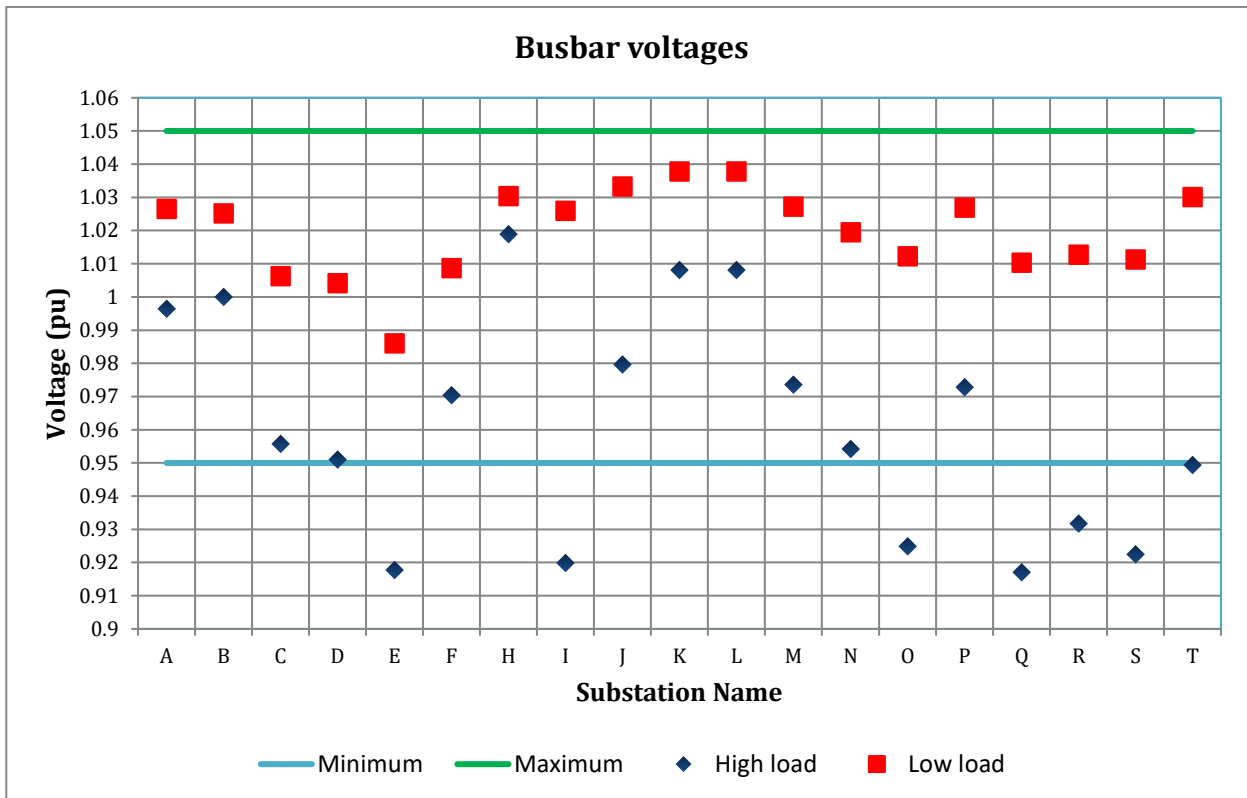


Figure 4.10: MTS1-MTS2 2029 voltage levels without DGs

MTS2-J branch

The results for the MTS2-J branch are shown in Figures 4.11 and 4.12 below.

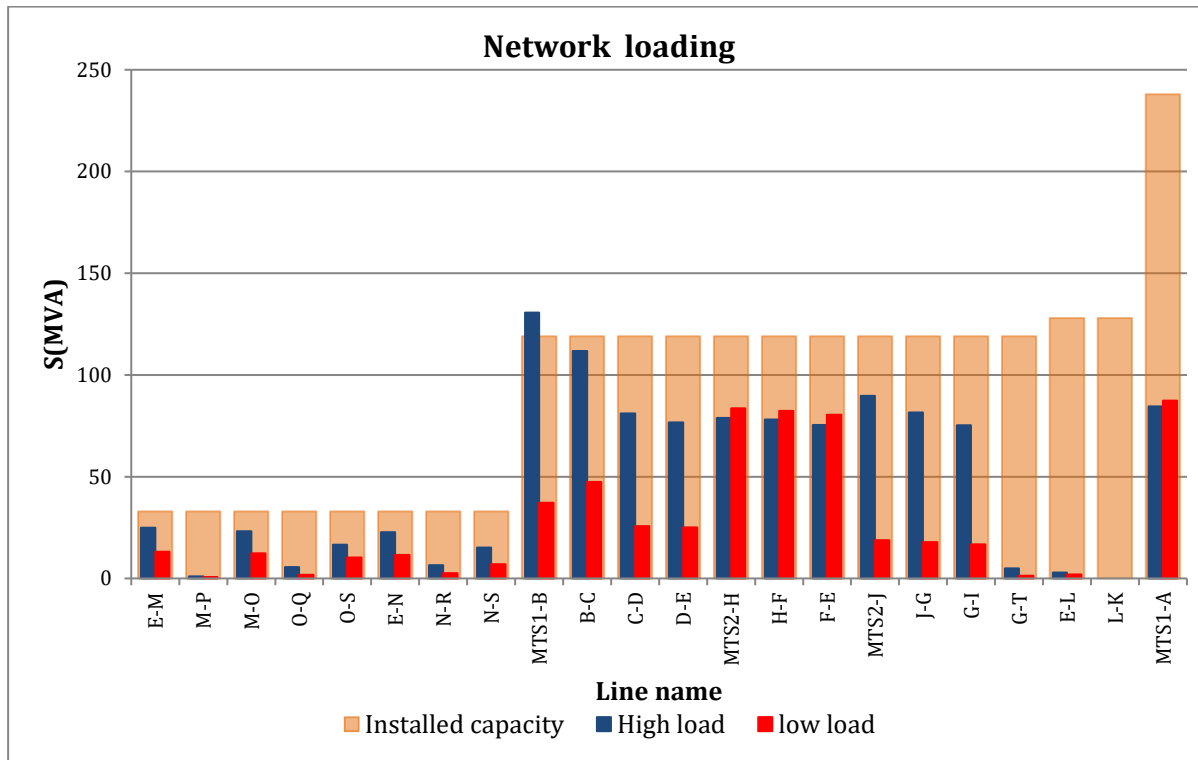


Figure 4.11: MTS2-J 2029 loading and installed capacities without DGs

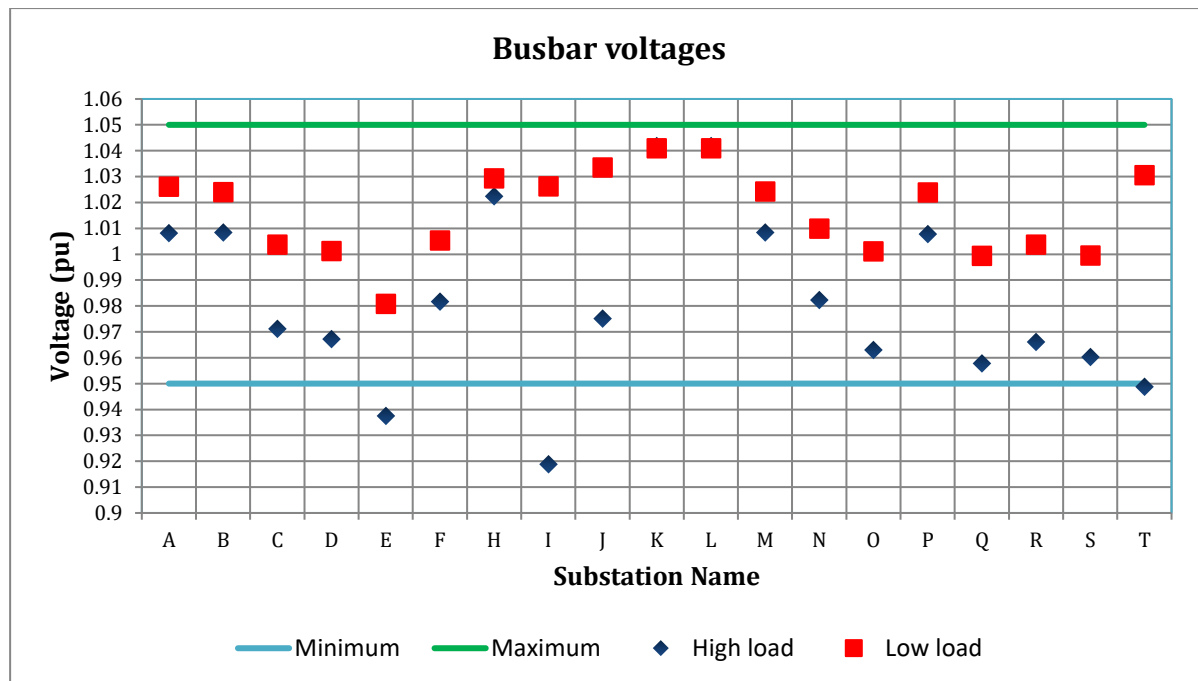


Figure 4.12: MTS2-J 2029 voltage levels without DGs

Thermal issues are anticipated on MTS2-B line section under high load conditions. This section is rated for 119.20 MVA but the simulated load on the line is expected to be 130.64 MVA. This is equivalent to 110% of the line thermal rating. Low voltages are also expected at substations E, I and T. The anticipated voltages at these substations are 0.9375 pu, 0.9188 pu and 0.9487 pu respectively. These voltages are below the 0.9500 pu limit as per the grid code. The reasons that have been stated above still hold. The expected network grid losses under high and low load conditions are 17.53 MW and 5.33 MW respectively.

4.2 Grid strengthening projects

Due to thermal and voltage constraints that are either existing or anticipated on the study network without DGs, there are strengthening projects that are required to be implemented to result in a grid code compliant network. Consequently, the network operator has evaluated different alternatives to alleviate the constraints on the network. These alternatives include establishment of new substations, shifting of load to adjacent networks, upgrading of the existing lines to bigger conductors, installation of shunt capacitors and construction of additional lines in parallel to the existing ones.

These alternatives have been evaluated technically by the network operator using DIGSILENT PowerFactory. In addition, the alternatives have also been evaluated financially using a financial modelling tool developed by the network operator. This tool takes into account the capital costs, maintenance and operation costs, cost of unserved energy during planned and unplanned outages, losses, inflation, interest rates and project life span before refurbishment or decommissioning is required. Having done a benefit to cost analysis for each alternative, the network operator has supported and approved two projects to be implemented on the network to alleviate thermal and voltage constraints that have been highlighted above. Since evaluation of different conventional strengthening alternatives does not form part of the research objectives, only a summary of high level scope and cost from the network operator's report will be given. The summary is as follows [50]:

- Construction of approximately 56 km 132 kV kingbird line, templated at 70 degrees from MTS2 to substation S and establishment of 132/66 kV 2 x 80 MVA substation at substation S. This project is expected to solve the thermal and voltage constraints on the MTS1-MTS2 branch once it is implemented as it will supply M, N, O, P,Q,R and S substations from the newly constructed 132/66 kV 2 x 80 MVA substation. It will therefore deload MTS1-MTS2 branch. This scenario will result in a reduced load on the MTS1-MTS2 branch and that will reduce loading on the conductors and also improve voltages on the network due to less voltage drop as a result of reduced load. A capital expenditure of about R243 million is required to execute the project. This cost has been taken from the network operator's report [50] and includes servitude and substation site costs, environmental approval administration costs, equipment costs and labour costs and is based on today's Rand value.

- Installation of 12 MVAR fixed shunt capacitor at substation I to solve the anticipated low voltages on the substations belonging to MTS2-J branch. The estimated cost to implement this project is about R15 million. This cost has been taken from the network operator's report [50] and includes equipment costs and labour costs and is based on today's rand value. No environmental administration costs, servitude and substation site costs are expected as the installation will utilise the existing space within the substation yard.

In summary, approximately R258 million is required to solve the expected problems on the study network.

4.3 Load flow studies with distributed generation

4.3.1 Analysis of 2019 loading and voltage levels with DGs

The load flow results for both high and low load conditions using real measured data are presented below for different branches.

MTS1-A branch

DGs that impact MTS1-A branch are:

- A 140 MW Wind Energy Farm at substation A. This plant produced 123 MW under high load and 137 MW under low load conditions.
- A 65 MW Wind Energy Farm at substation F. This plant produced 18 MW under high load and 37 MW under low load conditions.
- A 5 MW PV plant at substation K. This plant produced 4 MW under high load and 0 MW under low load conditions.

Collectively, the DGs contributed a generation of 145 MW and 174 MW under high load and low load respectively. The results for the MTS1-A branch which take into consideration the generation mentioned above at each substation are shown in Figures 4.13 and 4.14 below. Without distributed generation considered, no thermal constraints were evident from the results. However, low voltages at substation E were noticed. With distributed generation incorporated into the simulations, the voltage at substation E improves to 0.9531 pu. This is within the 0.9500-1.0500 pu range as per the grid code and consequently, no voltage issues were experienced on the network as DGs were generating during the MTS1-A peaking period. The improvement in voltage is due to wind energy farm F and solar plant K combined supplementary generation of 22 MVA which reduced electrical power requirements from the upstream network, thus reducing the upstream network load requirements which resulted in less voltage drop on the network.

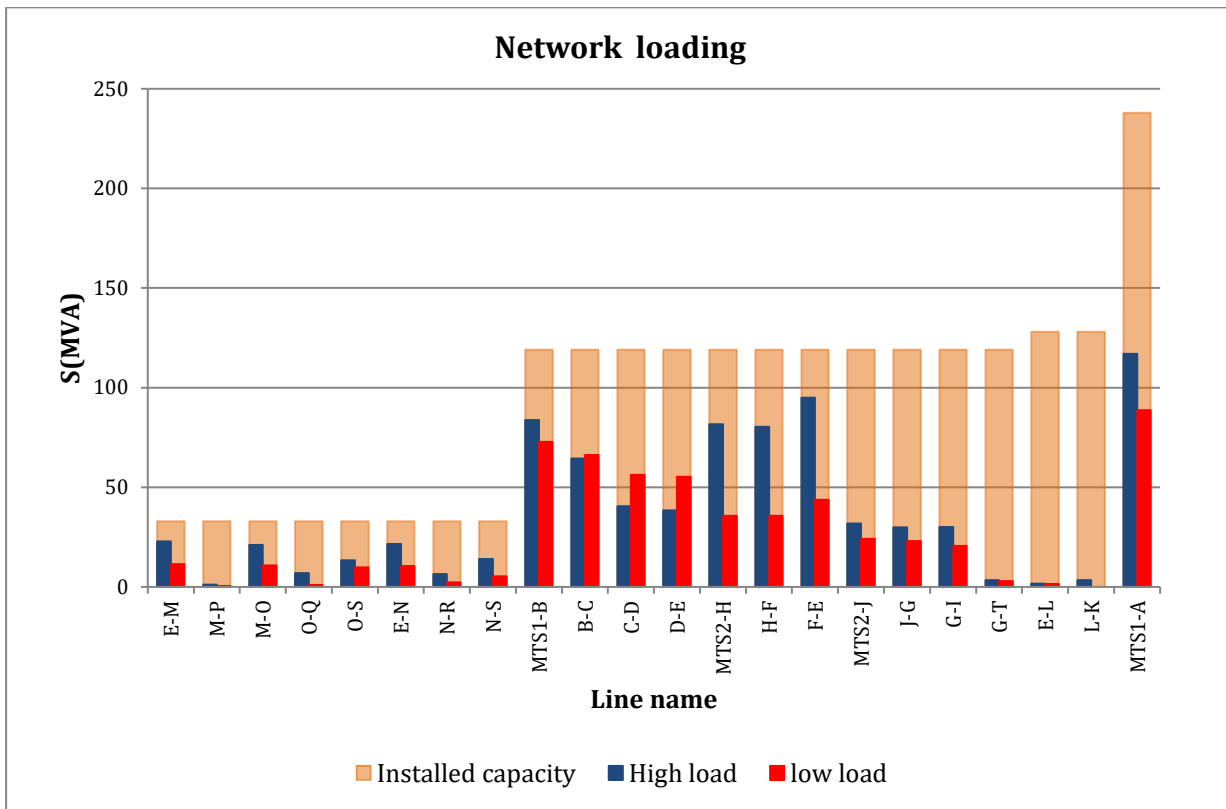


Figure 4.13: MTS1-A 2019 loading and installed capacities with DGs

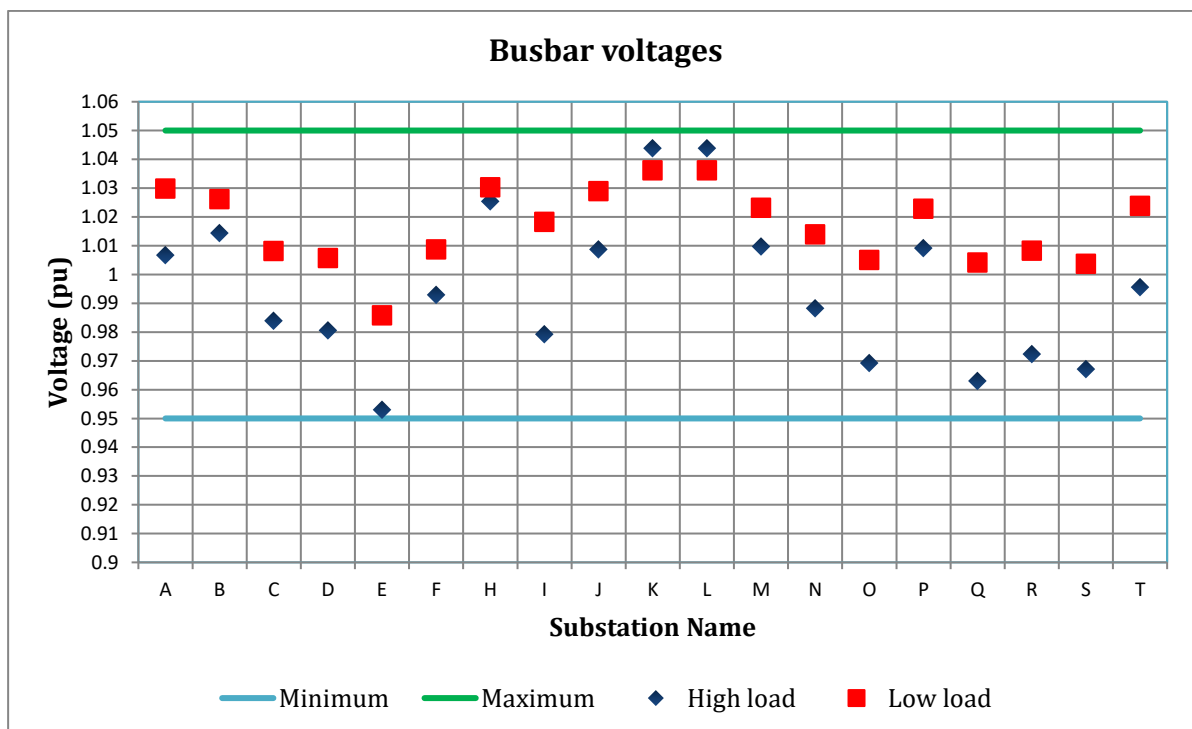


Figure 4.14: MTS1-A 2019 voltage levels with DGs

Furthermore, the network grid losses obtained from the simulations under high and low load conditions are 14.44 MW and 9.18 MW respectively. Network grid losses under high load conditions did not change significantly. This is despite having the MTS1-A branch load requirements being supplemented by 123 MVA from the wind generation plant A1 and thus reducing upstream network load requirements by at least 123 MVA. A contribution to the insignificant change is due to the fact that available generation on one of the branches with the biggest load (MTS1-MTS2) was only 19 MVA which is only about 11% of the branch load requirements. Most of the load was therefore still required to be supplied by MTS1 and MTS2 over a long distance. Due to losses being calculated as $P_{\text{loss}} = (I^2) \cdot R$ where I is the load and R is the resistance of the line, the long distance as well as the source being far away from the load centre attributed to insignificant change even with distributed generation considered. However, a significant change in losses under low load conditions is evident. Losses increased from 4.19 MW to 9.18 MW. This is equivalent to 120% increase. This increase is mainly due to load closer to the distributed generation source not being able to consume all the generation generated by the relevant plant. As a result, some generation need to be transported over long distances to nearby load centres.

MTS1-MTS2 branch

DGs that impact MTS1-MTS2 branch are:

- A 65 MW Wind Energy Farm at substation F. This plant produced 64 MW under high load and 61 MW under low load conditions.
- A 5 MW PV plant at substation K. This plant produced 4 MW under high load and 0 MW under low load conditions.

Collectively, the DGs contributed a generation of 68 MW and 61 MW under high load and low load respectively. The results for the MTS1-MTS2 branch which take into consideration the generation mentioned above at each substation are shown in Figures 4.15 and 4.16 below. MTS1-MTS2 simulation branch results without distributed generation showed thermal constraints on the MTS1-B and B-C line sections. These lines were loaded to 121% and 105% respectively. Low voltages were also evident at substations E and I. These substations experienced a low voltage of 0.9406 pu and 0.9466 pu respectively. With distributed generation incorporated, no thermal or voltage constraints are evident as illustrated in Figures 4.15 and 4.16. The reduction in line loading and improvement in substation voltages is due to injection of real and reactive power closer to the load which reduces load requirements from the upstream network.

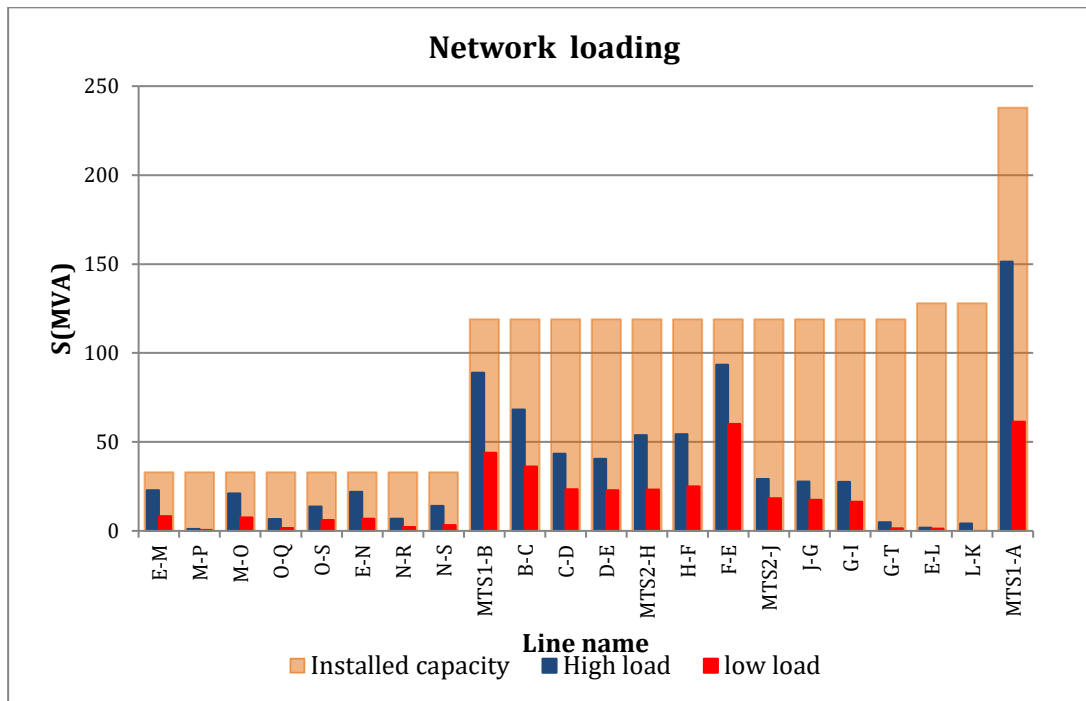


Figure 4.15: MTS1-MTS2 2019 loading and installed capacities with DGs

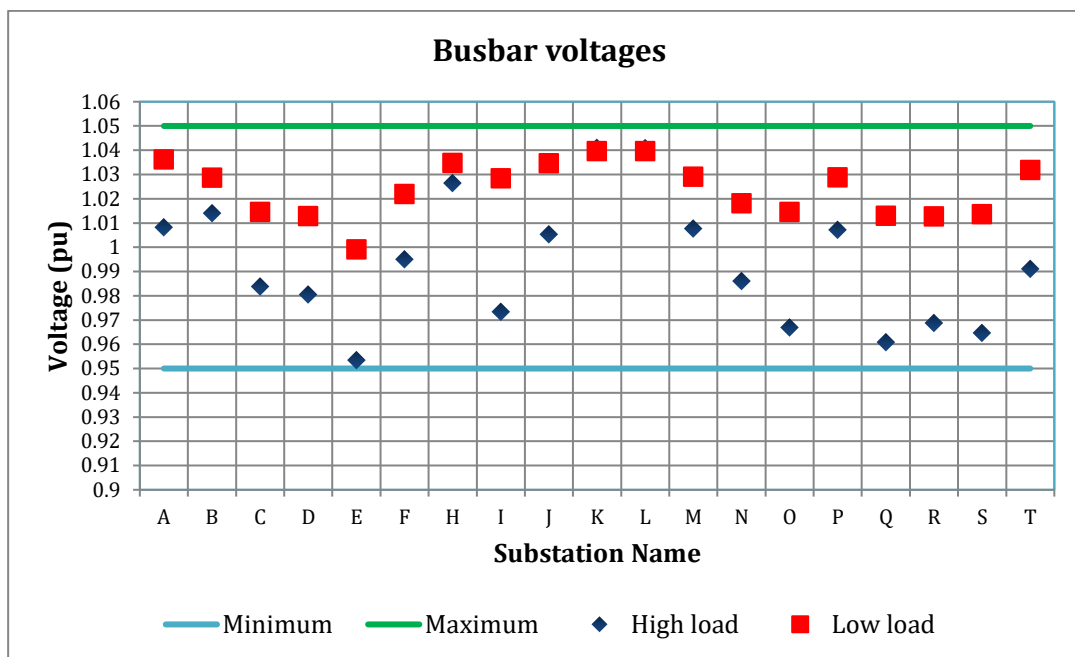


Figure 4.16: MTS1-MTS2 2019 voltage levels with DGs

Furthermore, the network grid losses obtained from the simulations under high and low load conditions are 12.28 MW and 6.67 MW respectively. This is reduction in losses from 16.70 MW to 12.28 MW (26% reduction in losses) under high load conditions and increase in losses from 3.76 MW to 6.67 MW (77% increase in losses) under low load conditions. The reduction in losses under high load conditions is due to some of the load which would have otherwise been supplied by either MTS1

or MTS2 being supplied by DGs closer to the load, thereby reducing load requirements from the upstream network which in turn result in reduction in losses. During MTS1-MTS2 branch peaking period, available supplementary generation on the branch was about 68 MVA. The generation is located very close to substation E which is the biggest load centre on the branch and this resulted in a significant reduction in losses being evident from the results. The increase in losses under low load conditions is due to the same reasons stated above under MTS1-A branch when considering distributed generation.

MTS2-J branch

DGs that impact MTS1-J branch are:

- A 65 MW Wind Energy Farm at substation F. This plant produced 5 MW under high load and 42 MW under low load conditions.
- A 5 MW PV plant at substation K. This plant produced 1 MW under high load and 0 MW under low load conditions.
- A 75 MW PV plant at substation I. This plant produced 73 MW under high load and 0 MW under low load conditions.
- A 9 MW PV plant at substation T. This plant produced 6 MW under high load and 0 MW under low load conditions.

Collectively, the DGs contributed a generation of 85 MW and 42 MW under high load and low load respectively. The results for the MTS1-J branch which take into consideration the generation mentioned above at each substation are shown Figures 4.17 and 4.18 below.

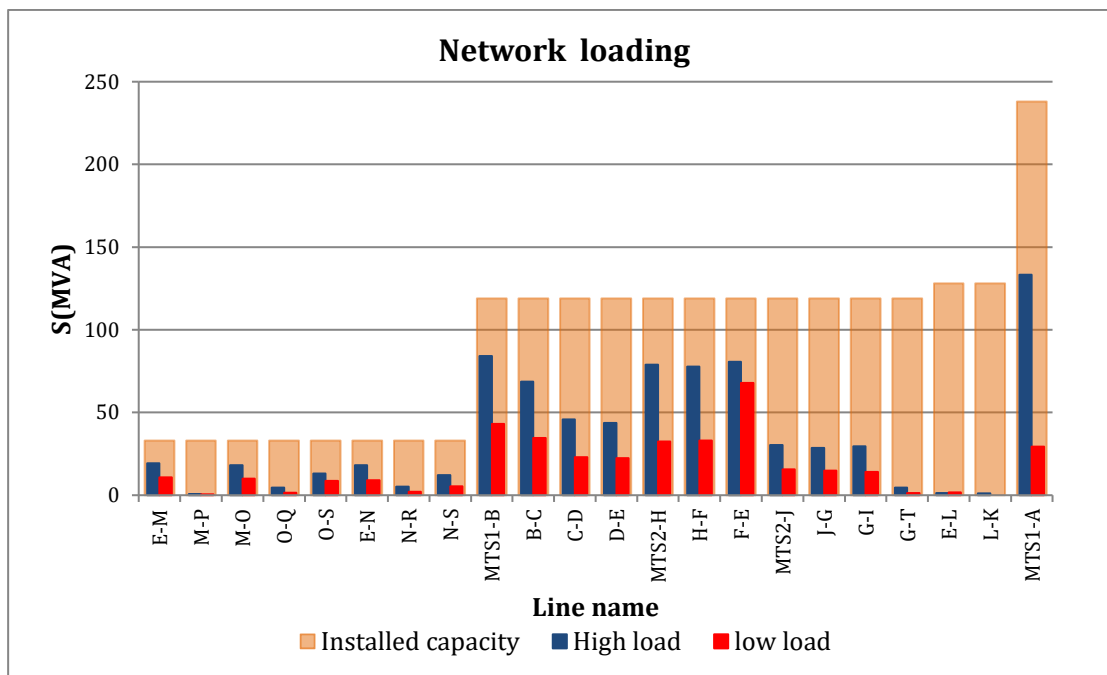


Figure 4.17: MTS2-J 2019 loading and installed capacities with DGs

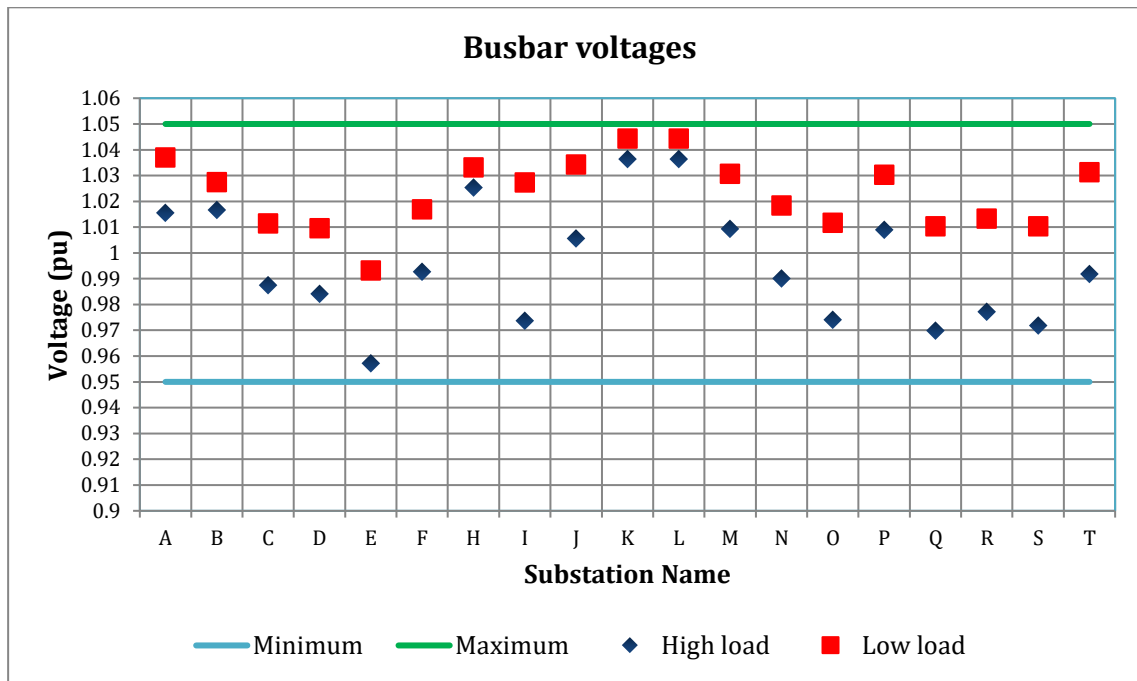


Figure 4.18: MTS2-J 2019 voltage levels with DGs

Low voltages were experienced at substation I when distributed generation was not considered. With distributed generation considered, no low voltages are evident from the results. In addition, network grid losses obtained from the simulations under high and low load conditions are 11.27 MW and 5.24 MW respectively. This is a slight decrease from 12.30 MW to 11.27 MW (6% reduction) under high load conditions and an increase from 4.45 MW to 5.24 MW (18% increase) under low load conditions. The reasons as stated above still hold.

4.3.2 Analysis of 2029 loading and voltage levels with DGs

MTS1-A branch

A summary of distributed generation forecast results for the MTS1-A branch is shown in Table 4.1. Detailed calculations can be found in the appendix section. The generators that directly impact MTS1-A branch are Gen A1 and Gen A2. The forecasted generation under high and low load conditions is about 27% and 57% respectively of the maximum generation. Generation from other wind farms within the study network averages at about 30% under both load and high load conditions. The PV plants on the other hand have the availability factor of at least 62% under high load conditions which is an advantage for this network since the peak is predominantly during the day when the sun is available. In addition, the PV plants are not generating under low load conditions since the scenario mostly occurs during early hours of the morning when the sun is not available

Table 4.1: MTS1-A DG forecast

Substation	Generation Name	Type	Maximum (MVA)	Availability Factor (%)		Forecasted Generation (MVA)	
				High Load	Low Load	High Load	Low Load
A	Gen A1	Wind	140.0	26.5	57.4	37.1	80.4
	Gen A2	Wind	140.0	26.5	57.4	37.1	80.4
E	Gen E	Wind	140.0	29.8	29.7	41.7	41.6
F	Gen F	Wind	65.4	29.8	29.7	19.5	19.4
I	Gen I	PV	75.0	73.4	0	55.1	0
K	Gen K1	PV	5.0	62.3	0	3.1	0
	Gen K2	PV	5.0	62.3	0	3.1	0
P	Gen P	Wind	8.4	29.8	29.7	2.5	2.5
T	Gen T	PV	9.5	72.1	0	6.8	0

The loading and voltage results for the MTS1-A branch assuming the generation as stipulated in Table 4.1 are shown in Figures 4.19 and 4.20 below.

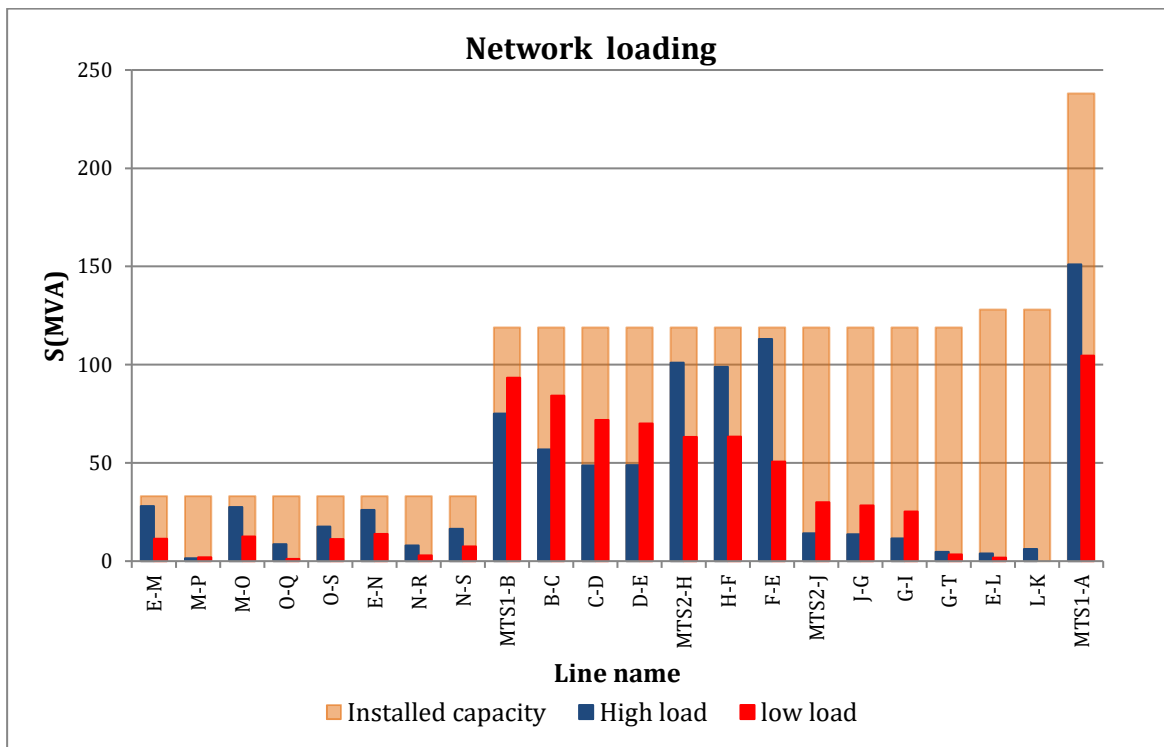


Figure 4.19: MTS1-A 2029 loading and installed capacities with DGs

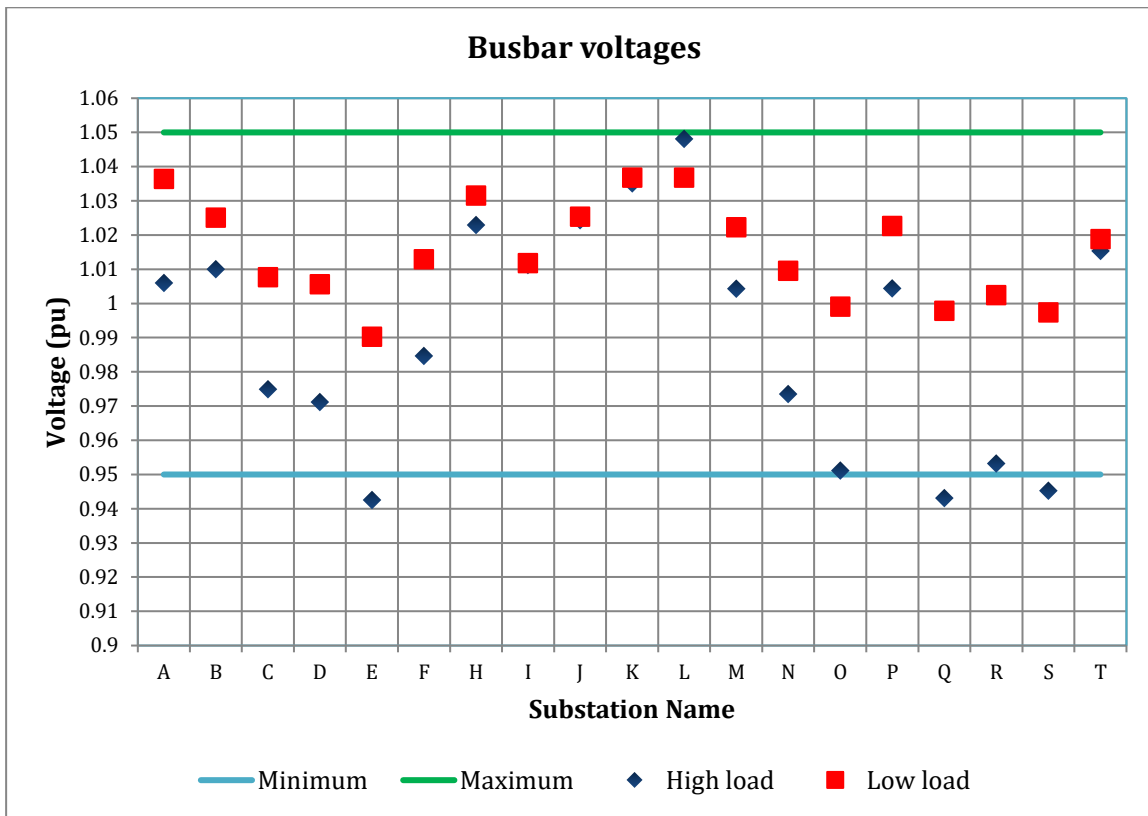


Figure 4.20: MTS1-A 2029 voltage levels with DGs

Results without distributed generation incorporated showed that thermal issues on MTS2-H, H-F and F-E line sections are expected under high load conditions. With distributed generation considered, no line is anticipated to be loaded above 100% of its thermal rating. In addition, simulations without distributed generation showed that low voltages are expected at substations E, I, O, Q, R and S. With distributed generation considered, no low voltages are expected at substations I, O and R. However, low voltages are still expected at substations E, Q and S. These substations are expected to experience low voltages of 0.9425 pu, 0.9431 pu and 0.9452 pu respectively. These low voltages are expected even with distributed generation considered because of inadequate generation availability on the MTS1-MTS2 branch during MTS1-A branch peaking period.

Even though low voltages are expected, there is evidence of voltage improvement with distributed generation considered from the 0.9237 pu, 0.9292 pu and 0.9351 pu results without distributed generation. However, the strengthening solution to result in a grid compliant network is no longer required to be as capital intensive as the solution that has been supported and approved by the network operator. Simulation results showed that voltages at E, Q and S improved to 0.9516 pu, 0.9531 pu and 0.9589 pu respectively with installation of a low cost strengthening solution such as 7.2MVAR shunt capacitor at substation S. Substation S has been chosen due to it being at the end of the network. Injection of reactive power at substation S reduces reactive power requirements from the upstream network which in turn reduces the apparent power and improves the voltages on the network. This solution can be realised at an estimated cost of R9 million. The cost has been obtained

from the network operator and is based on a recently completed project in the same area and it is based on today's rand value. Therefore, a saving of about R234 million (243-9 million) that would have otherwise been spent strengthening MTS1-MTS2 branch to ensure a grid compliant network can now be realised. The comparison of voltage levels at each substation before and after DG integration, and strengthening solution is illustrated in Table 4.2 below.

Table 4.2: Comparison of voltage levels at Substation before and after DG integration, and strengthening solution

Scenario	Voltage levels at Substations					
	E	I	O	Q	R	S
Without DG	Low	Low	Low	Low	Low	Low
With DG	Low	Normal	Normal	Low	Normal	Low
With Strengthening Solution	Normal	Normal	Normal	Normal	Normal	Normal

Furthermore, network grid losses under high and low load conditions are expected to be 15.41 MW and 11.55 MW respectively. This is reduction from 20.85 MW to 15.41 MW (26% reduction) under high load conditions and an increase from 5.08 MW to 11.55 MW (127% increase) under low load conditions. There was insignificant change in losses under high load conditions in 2019 with distributed generation included and this was due to very minimal generation on the branches with the biggest load. The reduction under high load is now significant due to the added 140 MW wind plant at substation A, 140 MW wind plant at substation E and 5 MW PV plant at substation K. This additional generation is closer to the substations with the biggest load and therefore result in significant reduction in network grid losses. The reasons given before for the increase in network grid losses under low load conditions still hold.

MTS1-MTS2 branch

A summary of distributed generation forecast results for the MTS1-MTS2 branch is shown in Table 4.3. Detailed calculations can be found in the appendix section. The generators that directly impact MTS1-MTS2 branch are Gen E, F, K1 and K2. The forecasted generation under high and low load conditions are at least about 64% and 53% respectively of the maximum generation. Generation from other wind farms within the study network also averages at about 17% under high load conditions and 33% under low load conditions. The PV plants on the other hand have the availability factor of at least 72% under high load conditions and not available under low load conditions and the reasons as stated before still hold.

Table 4.3: MTS1-MTS2 DG forecast

Substation	Generation Name	Type	Maximum (MVA)	Availability Factor (%)		Forecasted Gen (MVA)	
				High Load	Low Load	High Load	Low Load
A	Gen A1	Wind	140.0	17.0	33.4	23.8	46.8
	Gen A2	Wind	140.0	17.0	33.4	23.8	46.8
E	Gen E	Wind	140.0	64.6	53.3	90.4	74.6
F	Gen F	Wind	65.4	64.6	53.3	42.2	34.9
I	Gen I	PV	75.0	74.2	0	55.6	0
K	Gen K1	PV	5.0	72.4	0	3.6	0
	Gen K2	PV	5.0	72.4	0	3.6	0
P	Gen P	Wind	8.4	64.6	53.3	5.4	4.5
T	Gen T	PV	9.5	74.8	0	7.1	0

The loading, voltage and losses results for the MTS1-MTS2 branch assuming the generation as stipulated in Table 4.3 are shown in Figures 4.21 and 4.22 below.

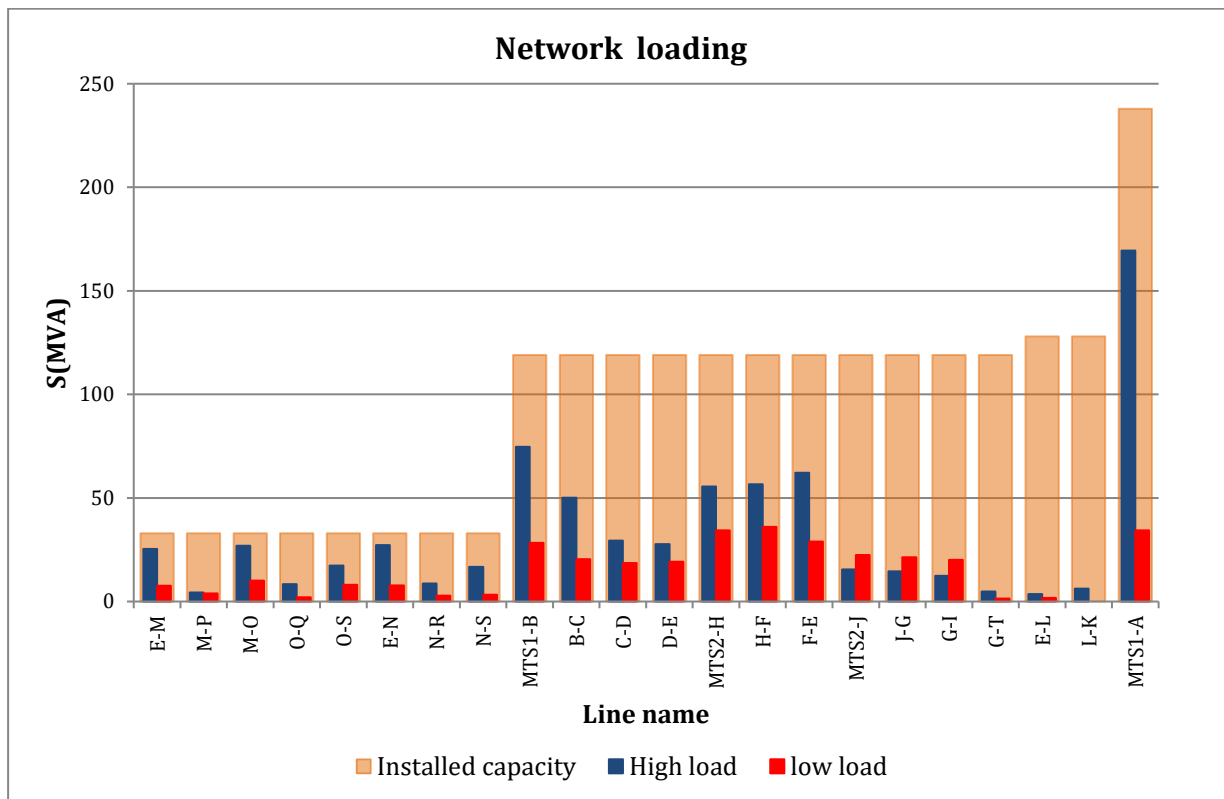


Figure 4.21: MTS1-MTS2 2029 loading and installed capacities with DGs

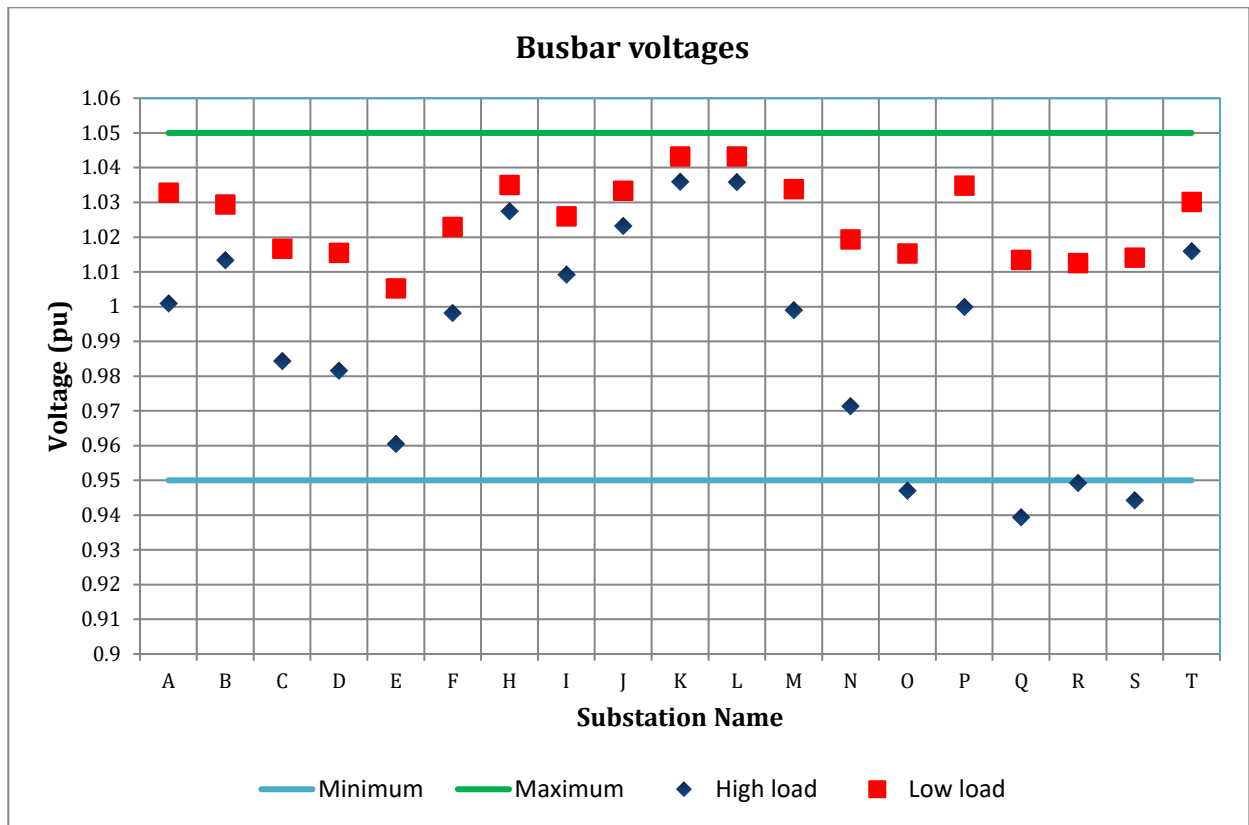


Figure 4.22: MTS1-MTS2 2029 voltage levels with DGs

Without distributed generation considered, thermal issues are anticipated on MTS2-B and B-C line sections under high load conditions. Low voltages are also expected at substations E, I, O, Q, R, S and T. With distributed generation considered, no thermal issues are expected. However, low voltages at substations O, Q, R and S are still expected. These substations are anticipated to have low voltages of 0.9470 pu, 0.9393 pu, 0.9492 pu and 0.9442 pu. The low voltage problem can however be solved by installation of 7.2 MVAR fixed shunt capacitor at substation S as stated before. With shunt capacitor installed, the voltages are expected to improve to at least 0.9700 pu. The reasoning that has been given before is still valid for this scenario as well. The comparison of voltage levels at each substation before and after DG integration, and strengthening solution is illustrated in Table 4.4 below.

Table 4.4: Comparison of voltage levels at Substation before and after DG integration, and strengthening solution

Scenario	Voltage levels at Substations						
	E	I	O	Q	R	S	T
Without DG	Low	Low	Low	Low	Low	Low	Low
With DG	Normal	Normal	Low	Low	Low	Low	Normal
With Strengthening Solution	Normal	Normal	Normal	Normal	Normal	Normal	Normal

Furthermore, network grid losses under high and low load conditions are expected to be 11.33 MW and 5.46 MW respectively. This is a reduction from 20.42 MW to 11.33 MW (52% reduction) under high load conditions and an increase from 4.37 MW to 5.46 MW (25% increase) under low load conditions. The reasons as stated before still hold

MTS2-J branch

A summary of the generation forecast results for the MTS1-J branch is shown in Table 4.5. Detailed calculations can be found in the appendix section. The generators that directly impact MTS1-J branch are Gen I and T. The forecasted generation of these generators under high load is at least 76% of the maximum generation. Other PV plants on the study network are expected to generate at least 68% of the installed generation during MTS2-I and J branch peaking period. Generation from the wind farms is expected to be at most 30% of the installed capacity under high load conditions and 46% under low load conditions.

Table 4.5: MTS2-J DG forecast

Substation	Generation Name	Type	Maximum (MVA)	Availability Factor (%)		Forecasted Generation (MVA)	
				High Load	Low Load	High Load	Low Load
A	Gen A1	Wind	140.0	3.6	46.4	5.0	65.1
	Gen A2	Wind	140.0	3.6	46.4	5.0	65.1
E	Gen E	Wind	140.0	30.2	34.2	42.3	47.9
F	Gen F	Wind	65.4	30.2	34.2	19.8	22.4
I	Gen I	PV	75.0	92.3	0	69.2	0
K	Gen K1	PV	5.0	68.5	0	3.4	0
	Gen K2	PV	5.0	68.5	0	3.4	0
P	Gen P	Wind	8.4	30.2	34.2	2.5	2.9
T	Gen T	PV	9.5	76.2	0	7.2	0

The loading, voltage and losses results for the MTS2-I and J branch assuming the generation as stipulated in Table 4.5 are shown in Figures 4.23 and 4.24 below.

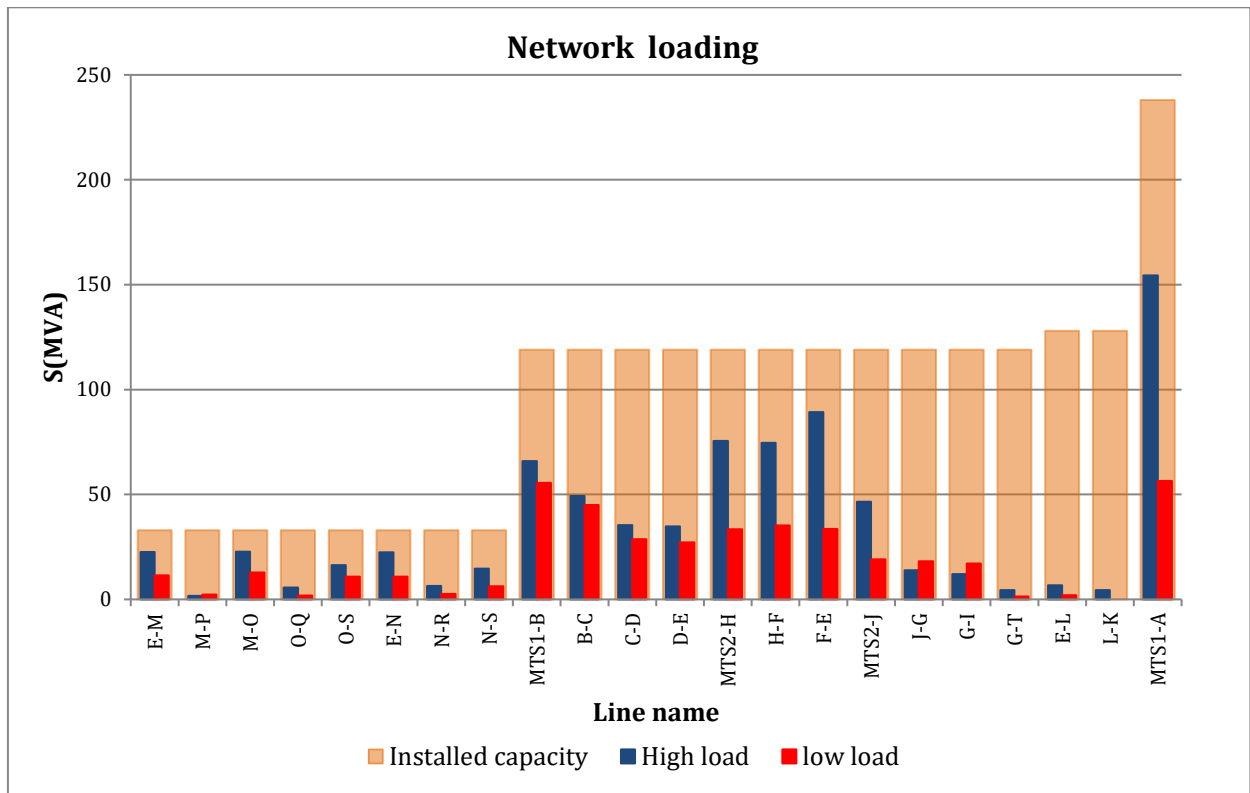


Figure 4.23: MTS2-J 2029 loading and installed capacities with DGs

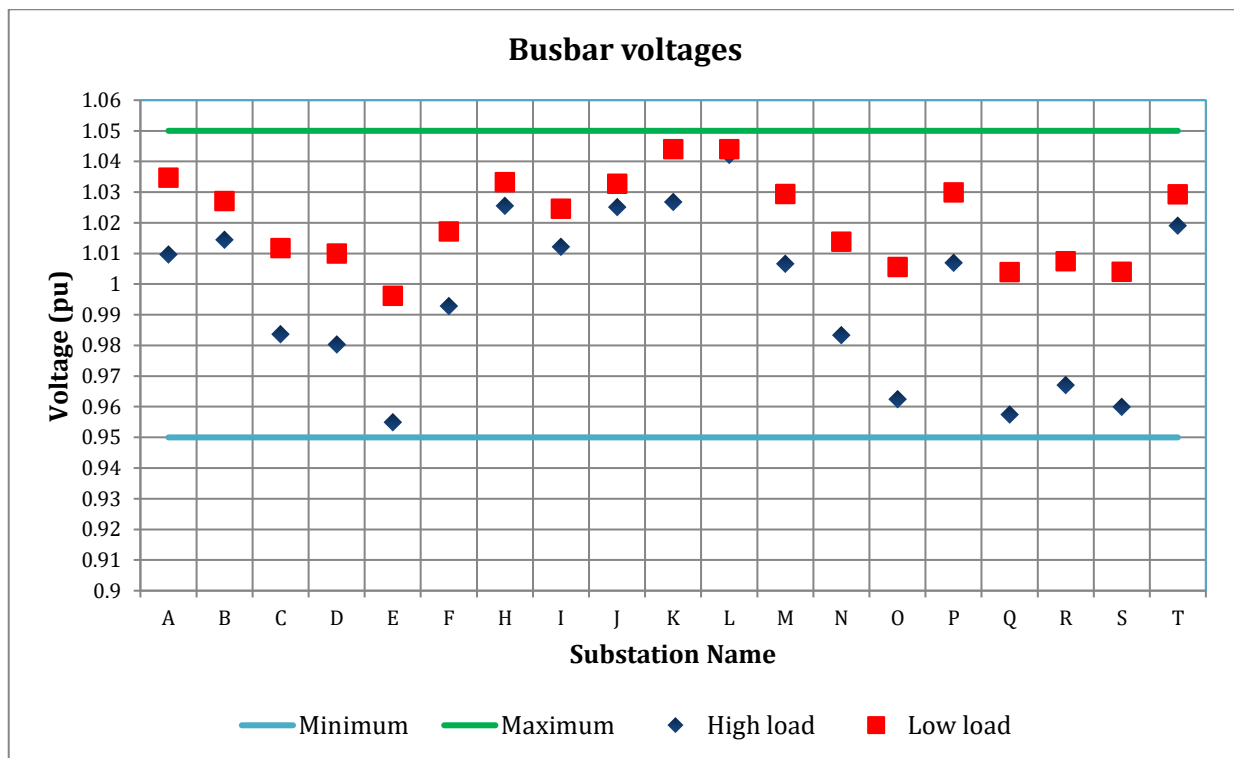


Figure 4.24: MTS2-J 2029 voltage levels with DGs

Without distributed generation considered, thermal issues are anticipated on MTS2-B line section under high load conditions. Low voltages are also expected at substations E, I and T. With distributed generation considered, no thermal or voltage issues are expected. In addition, network grid losses under high and low load conditions are expected to be 11.90 MW and 6.52 MW respectively. This is a reduction from 17.53 MW to 11.90 MW (32% reduction) under high load conditions and an increase from 5.33 MW to 6.52 MW (22% increase) under low load conditions. The reasons as stated before still hold. The comparison of voltage levels at each substation before and after DG integration, and strengthening solution is illustrated in Table 4.6 below.

Table 4.6: Comparison of voltage levels at Substation before and after DG integration, and strengthening solution

Scenario	Voltage levels at Substations		
	E	I	T
Without DG	Low	Low	Low
With DG	Normal	Normal	Normal
With Strengthening Solution	Not required	Not required	Not required

5 CONCLUSION

This report investigated the impact of distributed generation on power system grid planning to (i) check whether DG benefits deduced on a regulated market can also be realised from an unregulated market, (ii) analyse DG availability in relation to network load requirements to allow for future DG impact analysis and (iii) investigate whether incorporating future DG integration in distribution network planning can alleviate the financial ramifications of grid code compliance requirements.. The investigation was conducted using DIgSILENT PowerFactory simulation tool and a section of SA distribution network. Several assumptions were made to complete the study and based on the results contained in this report; the following conclusions can be drawn:

- Thermal and voltages constraints which would have been otherwise experienced under high load conditions in 2019 without distributed generation are not evident from the results when distributed generation is considered in the simulations.
- Thermal constraints that are expected to be experienced on the network in 2029 when distributed generation is not considered are not evident in the results when distributed generation is considered in the simulations.
- Low voltage constraints are still expected in 2029 even with distributed generation connected. These constraints however do not necessitate a capital expenditure of R258 million as previously stipulated. Simulations results showed that installation of 7.2 MVAR fixed shunt capacitor at an approximate cost of R9 million can result in a network being grid compliant. Therefore, a cost saving of about R249 million can be realised.
- There is evidence of reduction in losses under high load conditions and increase in losses under low load conditions. Reduction in losses is due to available generation during peaking period which reduces load requirements from the upstream network. Increase in losses is due to generation available being more than the local load requirements which result in excess generation being transported over long distances to the nearest load centres. These results suggest that both low and high load conditions need to be taken into consideration during sizing of the plant for optimum sizing.
- PV generation availability is higher than that of wind generation for the study network under high load conditions. This is particularly due to the fact that the network peaks predominantly during the day when PV generation is high. Wind generation availability is mostly high at night when the load is at its minimum. This observation suggests that it is not only the location, size and penetration level that is important for integration of DGs but also the correct selection of technology for a particular load type to maximize the benefits.
- The points given above prove that DG benefits that are realised on a regulated market can also be realised on an unregulated market. The benefits are dependent on the technology, size and location and will be unique for each network.

- The points above further prove that incorporating DG integration in distribution network planning can alleviate the financial ramifications of grid code compliance requirements.
- A very important conclusion drawn is that, results obtained from the simulations concur with the results obtained by previous researchers.

6 RECOMMENDATIONS

Based on the conclusions of the report, the following recommendations can be made:

- Distributed generation must be considered in the South Africa's power system grid planning process even though source of energy is intermittent to prevent network overdesign and unnecessary capital expenditure.
- There are techniques that have already been developed by other researchers for solar and wind energy forecasting. The network operator must utilise the relevant techniques to perform renewable generation forecasting to be able to perform future studies.
- This report made several generation forecasting assumptions to complete the study. This network must be studied again using a detailed generation forecast to see if the results contained in the report still hold.
- Department of Energy must empower the network operator to influence location, size, technology and penetration level to maximise the benefits of DGs on the SA network. The network operator's involvement in the policy drafting of the DG integration including customer initiated DG projects (i.e rooftop PV) is required to ensure safe operation of the network.
- Different scenarios (low, likely, high) must be thoroughly evaluated in the distribution network development plan to identify and manage risks associated with (i) not realizing the expected future DG penetration levels, (ii) exceeding the DG forecast and (iii) high penetration of Small Scale Embedded Generation (SSEG).

REFERENCES

- [1] Y. Haung, "Electricity Distribution Network Planning Considering Distributed Generation," KTH School of Electrical Engineering, Stockholm, Sweden, Thesis, 2014.
- [2] R. S. C. Camargos, R. A. Shayani and M. A. G. d. Oliveira, "Evaluating whether photovoltaic distributed generation postpones or anticipates reinforcements detected by distribution network expansion planning," *The Institute of Engineering and Technology*, vol. 13, no. 7, pp. 1036-1048, 2019.
- [3] M. A. H. El-Sayed and A. A. Arram, "Dispersed generation impact on distribution network expansion planning," in *Power Systems*, Clemson, SC, USA, 2009.
- [4] N. E. Matute, S. P. Torres and C. A. Castro, "Transmission Expansion Planning Considering the Impact of Distributed Generation," in *Innovative Smart Grid Technologies Europe*, Bucharest, Romania, 2019.
- [5] A. Piccolo and P. Siano, "Evaluating the Impact of Network Investment Deferral on Distributed Generation Expansion," *Transactions on Power Systems*, vol. 24, no. 3, pp. 1559-1567, 2009.
- [6] P. V. Gomes and J. T. Saraiva, "Transmission system planning considering solar distributed generation penetration," in *International Conference on the European Energy Market*, Dresden, Germany, 2017.
- [7] J. H. Zhao, J. Foster, Z. Y. Dong and K. P. Wong, "Flexible Transmission Network Planning Considering Distributed Generation Impacts," *Transactions on Power Systems*, vol. 26, no. 3, pp. 1434-1443, 2011.
- [8] Y. Zhang, C. Gu and F. Li, "Evaluation of investment deferral resulting from microgeneration for EHV distribution networks," in *PES General Meeting*, Providence, RI, USA, 2010.
- [9] D.-C. Wang, L. Ochoa, G. Harrison, C. Dent and A. Wallace, "Evaluating investment deferral by incorporating distributed generation in distribution network planning," in *Power System Computation Conference*, Glasgow, Scotland, 2008.
- [10] V. Mendez, J. Rivier, J. I. de la Fuente, T. Gomez, J. Arceluz, J. Marin and A. Madurga, "Impact of distributed generation on distribution investment deferral," *Electric Power & Energy Systems*, vol. 28, no. 4, pp. 244-252, 2006.
- [11] J. Bebic, "Power System Planning: Emerging Practices Suitable for Evaluating the Impact of High-Penetration Photovoltaics," National Renewable Energy Laboratory, Colorado, USA, 2008.

- [12] S. Krishna, *An introduction to Modelling of Power System Components*, India: Springer, 2014.
- [13] A. M. Al-Shaalan, "Essential aspects of power system planning in developing countries," *Journal of King Saud University-Engineering Sciences*, vol. 1, no. 23, pp. 27-32, 2011.
- [14] Eskom, "Process Control Manual for Strategic Network Planning," Centre of Excellence, Eskom, South Africa, 2014.
- [15] A. Covarrubias, "Expansion Planning for Electrical Power Systems," International Atomic Energy Agency, Austria, 1979.
- [16] J. Farrell, "The Challenge of Reconciling a Centralized v. Decentralized Electricity System," Institute For Local Self-Reliance, 17 October 2011. [Online]. Available: <https://ilsr.org/challenge-reconciling-centralized-v-decentralized-electricity-system/>. [Accessed 09 December 2020].
- [17] A. F. Sarabia, "Impact of distributed generation on distribution systems," Faculty of Engineering, Science and Medicine, Aalborg University, Aalborg, Denmark, MSc, June 2011.
- [18] S. Cox, P. Gagnon, S. Stout, O. Zinaman, A. Watson and E. Hotchkiss, "Distributed generation to support development-focused climate action," National Renewable Energy Laboratory, Denver, USA, September 2016.
- [19] R. A. Jerin, A. Jayakumar, J. Prabaharan, N. Palanisamy, K. Umashankar, S. and Thirumoorthy, A. D, "Frequency Control of a Stand Alone Hybrid Wind and Solar Based Distributed Generation System through an Optimized Energy Storage," in *International Conference on innovative Strategies in Renewable Energy and its applications*, Salem, India, 2015.
- [20] WEI-Khattam and M.M.A.Salama, "Distributed generation technologies, definitions and benefits," *Electric Power Systems Research*, vol. 71, no. 2, pp. 119-128, 2004.
- [21] IRENA, "International Renewable Energy Agency," [Online]. Available: <https://www.irena.org/wind>. [Accessed 17 December 2020].
- [22] J. McCloy, "Green Coast," 17 September 2019. [Online]. Available: <https://greencoast.org/onshore-vs-offshore-wind/#:~:text=Onshore%20wind%20is%20the%20one,the%20land%20towards%20the%20sea.&text=The%20result%20of%20this%20is,the%20land%20towards%20the%20sea..> [Accessed 2017 December 2020].

- [23] M. Bello, "Network & Grid Planning Standard for Generation Grid Connection-Generators Technology Overview and Effects on Networks," Centre of Excellence, Eskom, Midrand, South Africa, 2014.
- [24] United States Environmental Protection Agency, "A student guide to Global Climate Change," US EPA, 5 September 2017. [Online]. Available: <https://archive.epa.gov/climatechange/kids/solutions/technologies/wind.html>. [Accessed 17 December 2020].
- [25] H. Wagner, "Introduction to wind energy systems," in *EPJ Web of Conferences*, Bochum, Germany, 2017.
- [26] K. Folly, "Embedded Generation," University of Cape Town, Cape Town, South Africa, 2013.
- [27] Y. Zou, "Induction Generator in Wind Power Systems," in *Induction Motors-Applications, Control and Fault Diagnosis*, London, United Kingdom, IntechOpen Limited, 2015.
- [28] W. Freitas, J. C. M. Vieira, A. Morelato, L. C. P. d. Silva, i. F. d. Costa and F. A. B. Lemos, "Comparative Analysis Between Synchronous and Induction Machines for Distributed Generation Applications," *Transactions on Power Systems*, vol. 21, no. 1, pp. 301-311, 2006.
- [29] Wind Energy Technologies Office, "Energy Efficiency and Renewable Energy," US Department of Energy, [Online]. Available: <https://www.energy.gov/eere/wind/advantages-and-challenges-wind-energy>. [Accessed 21 December 2020].
- [30] Energysage, "Smart energy decisions," Energysage, LLC, [Online]. Available: <https://www.energysage.com/solar/>. [Accessed 21 December 2020].
- [31] N. M. Kumar M, S. P. Subathra and E. Moses, "On-Grid Solar Photovoltaic System: Components, Design Considerations, and Case Study," in *4th IEEE International Conference on Electrical Energy Systems*, Chennai, India, 2018.
- [32] Florida Solar Energy Centre, University of Central Florida, 2014. [Online]. Available: http://www.fsec.ucf.edu/en/consumer/solar_electricity/basics/types_of_pv.htm#:~:text=The%20two%20principal%20classifications%20are,systems%20and%20stand%20alone%20systems.&text=Grid%20connected%20or%20utility%20interactive%20PV%20systems%20are%20designed%20. [Accessed 22 December 2020].
- [33] Solar Electric Power Company, SEPCO, 26 January 2012. [Online]. Available: <https://www.sepco-solarlighting.com/blog/bid/115086/solar-power-advantages-and-disadvantages>. [Accessed 22 December 2020].

- [34] P.A.Daly and J. Morrison, "Understanding the potential benefits of distributed generation on power delivery systems," in *Rural Electric Power Conference*, Little Rock, Arkansas, USA, 2001.
- [35] E. S. Elmubarak and A. M. Ali, "Distributed Generation: Definitions, Benefits, Technologies & Challenges," *International Journal of Science and Research*, vol. 5, no. 7, pp. 1941-1948, July 2016.
- [36] F. S. Ma and D. H. Curtice, "Distribution Planning and Operations with Intermittent Power Production," *IEEE Transactions on Power Apparatus and Systems*, Vols. PAS-101, no. 8, pp. 2931-2940, 1982.
- [37] M. Saad, M.A. Tofigh, F. Zaheeda, A.N. AL-Masri, N.B. Othman, M. Irsyad, A. Abbas and E. Youssef "Design And Modeling An Automated Digsilent Power System For Optimal New Load Locations," *International Journal of Scientific and Technology Research*, vol. 4, no. 8, pp. 1-7, 2015.
- [38] DIgSILENT, "DIgSILENT PowerFactory," [Online]. Available: <https://www.digsilent.de/en/load-flow-analysis.html>. [Accessed 24 January 2021].
- [39] M. D. Smith, "MIT," 01 October 1998. [Online]. Available: https://web.mit.edu/10.001/Web/Course_Notes/NLAE/node6.html. [Accessed 24 January 2021].
- [40] A. Sharma, M. Saini and M. Ahmed, "Power Flow Analysis using NR Method," in *International Conference on Innovative Research in Science, Technology and Management*, Kota, Rajasthan, India, 2017.
- [41] National Energy Regulator of South Africa, "The South African Grid Code-The Network Code Version 7.0," NERSA, Pretoria, March 2008.
- [42] M. Bello and A. Ramdhin, "Network and Grid Planning Standard for Generation Grid Connection-Application for Planning Studies," Eskom Centre of Excellence, Midrand, October 2019.
- [43] M. Ghofrani and M. Alolayam, "Time Series and Renewable Energy Forecasting," in *Time Series Analysis and Application*, Washington, ScienceOpen, Inc., 2018, pp. 77-92.
- [44] David B. Alencar, C. Affonso, R. C. L. d. Oliveira, J. L. Rodríguez, J. C. Leite and J. C. R. Filho, "Different Models for Forecasting Wind Power Generation: Case Study," *Energies*, vol. 10, no. 12, pp. 2-27, 2017.
- [45] M. Haddad, J. Nicod, Y. B. Mainassara, L. Rabehasaina, Z. A. Masry and M. Péra, "Wind and Solar Forecasting for Renewable Energy System using SARIMA-based Model," in *International conference on Time Series and Forecasting*, Gran Canaria, Spain, September 2019.

- [46] J. Lima, J. Barata, M. Fernandez and A. Montiel, "The Distributed Generation as an Important Contribution to Energy Development in Angola and Other Developing African Countries," in *5th Doctoral Conference on Computing, Electrical and Industrial Systems (DoCEIS)*, April 2014, Costa de Caparica, Portugal. Pp.269-276.
- [47] J.Driesen and R.Belmans, "Distributed Generation: Challenges and Possible Solutions," in *IEEE Power Engineering Society General Meeting*, Montreal, QC, Canada, 2006.
- [48] Zero Point Energy, "Distributed Generation and the Key Enabling Role for Rural and Off-grid Applications in Southern Africa," Zero Point Energy (Pty) Ltd, Johannesburg, South Africa, 17 September 2019.
- [49] Green Rhino Energy, "Wind Energy Systems and Wind Farms: Components of a Wind Turbine," Green Rhino Energy Ltd, London, United Kingdom, 2016.
- [50] M. Kakaza and S. Coetzee, "Moorreesburg Network Development Plan," Network Planning, Western Cape Operating Unit, Eskom, Cape Town, South Africa, 2018.
- [51] M. Kakaza and K.A. Folly, "Effect of solar water heating system in reducing household energy consumption," in *Proceedings of 9th IFAC Symposium on Control of Power and Energy Systems (CPES-2015)*, New Delhi, Spain, December 2015.
- [52] Department of Mineral Resources and Energy, "Integrated Resource Plan (IRP2019)," Energy department, Republic of South Africa, Pretoria, October 2019.

APPENDICES

Appendix A: Raw data

	2019								Without Generation		2029							
	High2	Minimum	Maximum	low2	High1	Low1	High3	Low3	High1	Low1	High2	Low2	High3	Low3	7.2MVAR	7.2MVAR		
A	100.82	95	105	103.62	100.68	103.59	101.55	103.7										
B	101.4	95	105	102.87	101.44	102.63	101.66	102.74										
C	98.38	95	105	101.45	98.4	100.92	98.74	101.14										
D	98.05	95	105	101.29	98.06	100.71	98.41	100.95										
E	95.35	95	105	99.91	95.31	98.95	95.71	99.32						95.16				
F	99.5	95	105	102.2	99.3	101.41	99.26	101.68										
H	102.64	95	105	103.48	102.54	103.21	102.53	103.31										
I	97.34	95	105	102.84	97.93	101.73	97.37	102.73										
J	100.53	95	105	103.46	100.88	102.84	100.56	103.42										
K	104.09	95	105	103.96	104.39	103.84	103.64	104.43										
L	104.08	95	105	103.96	104.39	103.84	103.64	104.43										
M	100.77	95	105	102.91	100.98	102.33	100.93	103.06										
N	98.6	95	105	101.81	98.83	100.93	99	101.83										
O	96.69	95	105	101.45	96.93	100.27	97.4	101.16										
P	100.71	95	105	102.88	100.92	102.3	100.89	103.03										
Q	96.09	95	105	101.3	96.31	100.18	96.98	101.03										
R	96.87	95	105	101.27	97.24	100.36	97.71	101.33						95.31	99.53			
S	96.47	95	105	101.36	96.72	100.13	97.18	101.03						95.89	99.41			
T	99.1	95	105	103.19	99.56	102.3	99.18	103.13										

	2019								With Generation		2029							
	High2	Low2		High1	Low1	High3	Low3	High1	Low1	High2	Low2	High3	Low3					
E-M	22.92	33	8.23	22.77	11.48	19.37	10.72	28.06	11.36	25.34	7.62	22.62	11.44					
M-P	1.15	33	0.57	1.13	0.55	0.8	0.55	1.51	1.96	4.36	3.88	1.77	2.33					
M-D	21.11	33	7.66	20.99	10.84	18.12	10.1	27.52	12.54	27.01	10.08	22.78	12.84					
D-Q	6.68	33	1.63	6.94	0.95	4.53	1.46	8.66	1.19	8.33	2.03	5.64	1.82					
D-S	13.74	33	6.06	13.38	9.81	13.12	8.58	17.56	11.24	17.33	8.03	16.27	10.86					
E-N	22.02	33	6.92	21.47	10.48	18.1	9.02	26.03	13.85	27.2	7.83	22.42	10.85					
N-R	6.88	33	2.26	6.39	2.29	5.2	2.12	8	2.87	8.63	2.83	6.5	2.65					
N-S	14.06	33	3.28	14.07	5.39	12.22	5.38	16.47	7.43	16.75	3.29	14.73	6.28					
MTS1-B	88.94	119	43.97	83.8	72.76	84.2	43.13	75.1	93.28	74.72	28.26	65.86	55.63					
B-C	68.3	119	36.2	64.38	66.17	68.7	34.58	56.8	84.2	50.07	20.52	49.27	45.06					
C-D	43.34	119	23.42	40.56	56.24	45.73	23	48.72	71.91	29.47	18.58	35.35	28.76					
D-E	40.59	119	22.79	38.34	55.26	43.69	22.44	48.94	70.04	27.78	19.27	34.82	27.14					
MTS2-H	53.91	119	23.23	81.65	35.64	78.83	32.41	101.04	63.27	55.5	34.29	75.62	33.36					
H-F	54.28	119	24.99	80.32	35.76	77.72	32.99	98.85	63.34	56.55	36.13	74.66	35.25					
F-E	93.45	119	60.09	95	43.77	80.75	67.97	113.12	50.59	62.21	29.02	89.34	33.63					
MTS2-J	29.12	119	18.31	31.84	24.15	30.29	15.56	14.14	29.94	15.47	22.46	46.62	19.06					
J-G	27.75	119	17.48	29.92	22.96	28.63	14.91	13.75	28.28	14.53	21.42	13.86	18.2					
G-I	27.6	119	16.39	30.1	20.56	29.54	14.03	11.62	25.28	12.44	20.08	12.07	17.11					
G-T	4.96	119	1.4	3.41	2.85	4.53	1.3	4.73	3.33	4.89	1.49	4.42	1.38					
E-L	1.88	128	1.36	1.6	1.45	1.36	1.61	3.91	1.82	3.63	1.7	6.76	2.02					
L-K	4.08	128	0	3.37	0	1.03	0	6.16	0	6.16	0	4.37	0					
MTS1-A	151.3	238	61.38	117.01	88.76	133.29	29.3	151.11	104.68	169.42	34.32	154.36	56.42					

Appendix B: Load Forecast

	Peak			Peak			Peak	
	2019	2029		2019	2029		2019	2029
A	177.1	214	B	20.62	22.45	I	56.9	70.3
SF		1.20835686	C	26.43	29.9	J	3.68	4.3
			D	4.5	8.6	T11	3.02	3.02
			E	68.02	72	T22	2.61	4.98
			F	0	0		66.21	82.6
			H	1.63	15	Actual	63	78.59538
			K	0	0	Diversity	0.951518	
			L	3.31	4.2	SF	1.247546	
			M	0	0			
			N	3.72	5.5			
			O	0	0			
			P	1.35	1.8			
			Q	7.14	11			
			R	6.68	8.7			
			S	27.93	35.6			
				171.33	214.75			
			Peak	174	211.4547			
			Diversity	0.984655				
			Scaling Factor	1.234195				

Appendix C: Generation Forecast

		MTS1-A branch									
	GenA	Gen F	Gen K	Gen I	Gen T		GenA	Gen F	Gen K	Gen I	Gen T
max gen (MVA)	140	65.4	5	75	9		140	65.4	5	75	9
Branch Peak date						Low load date					
06/02/2019 16:00	123.1	17.5	3.4	48.8	6.3	21/04/2019 02:00	137.3	36.5	0	0	0
13/03/2018 15:00	6.52	7.65	1.83	55.03	7.09	24/09/2018 03:00	56.45	10.7	0	0	0
23/02/2017 15:00	8.47	22.55	3.65	61.23	7.73	05/11/2017 02:00	67.07	15.19	0	0	0
01/02/2016 15:00	10.56	30.34	3.58		4.83	27/03/2016 04:00	60.79	15.27	0	0	0
Aggregate value	37.1625	19.51	3.115	55.02	6.4875	Aggregate value	80.4025	19.415	0	0	0
Availability Factor	26.54464	29.8318	62.3	73.36	72.08333	Availability Factor	57.43036	29.68654	0	0	0

		MTS1-MTS2 branch									
	GenA	Gen F	Gen K	Gen I	Gen T		GenA	Gen F	Gen K	Gen I	Gen T
max gen (MVA)	140	65.4	5	75	9		140	65.4	5	75	9
Branch Peak date						Low load date					
07/02/2019 15:00	22.99	63.46	4.14	65.81	7.96	30/07/2019 03:00	122.94	60.78	0	0	0
07/02/2018 16:00	1.72	20.94	3.49	50.88	6.32	02/07/2018 03:00	21.78	33.57	0	0	0
08/03/2017 16:00	48.78	65.17	3.36	50.19	6.27	03/11/2017 02:00	7.32	34.18	0	0	0
20/00/2016 16:00	21.74	19.44	3.49		6.38	31/12/2016 05:00	34.94	10.82	0	0	0
Aggregate value	23.8075	42.2525	3.62	55.62667	6.7325	Aggregate value	46.745	34.8375	0	0	0
Availability Factor	17.00536	64.60627	72.4	74.16889	74.80556	Availability Factor	33.38929	53.26835	0	0	0

		MTS1-I and J branch									
	GenA	Gen F	Gen K	Gen I	Gen T		GenA	Gen F	Gen K	Gen I	Gen T
max gen (MVA)	140	65.4	5	75	9		140	65.4	5	75	9
Branch Peak date						Low load date					
07/03/2019 12:00	1.99	5.33	1.04	72.89	6.3	24/07/2019 04:00	94.25	41.99	0	0	0
29/01/2018 12:00	1.79	13.03	4.39	69.25	7.78	19/06/2018 02:00	29.27	13.97	0	0	0
18/01/2017 12:00	6.02	30.36	4.69	65.51	8.53	12/07/2017 03:00	120.15	30.94	0	0	0
01/02/2016 15:00	10.56	30.34	3.58		4.83	20/06/2016 02:00	16.13	2.58	0	0	0
Aggregate value	5.09	19.765	3.425	69.21667	6.86	Aggregate value	64.95	22.37	0	0	0
Availability Factor	3.635714	30.22171	68.5	92.28889	76.22222	Availability Factor	46.39286	34.20489	0	0	0