



ADDIS ABABA UNIVERSITY
SCHOOL OF GRADUATE STUDIES
INSTITUTE OF TECHNOLOGY
DEPARTMENT OF
ELECTRICAL AND COMPUTER ENGINEERING
OPTIMAL LOCATION AND SIZING OF DISTRIBUTED GENERATION

The Case Study of Adama Distribution System

A thesis submitted to the school of graduate studies of Addis Ababa University in partial fulfillment of the requirements for the degree of Masters of Science in Electrical Engineering (Electrical Power Engineering)

By

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Abstract

Integrating distributed generation (DG) to an existing distribution system delivers various profits for both utility and end users. Distributed generation provides a means to beat incremental increase in energy demand, to improve distribution system reliability and decrease power loss by generating electric power at the distribution system.

Distributed generation is a developing idea in the electricity sector, which represents good choices for electricity supply instead of the old centralized power generation concept. The introduction of DG leads to a fundamental modification in how distribution networks are utilized and observed. Distribution networks are now used as a means to connect geographically dispersed energy sources to the electricity system; thereby converting what were originally energy delivery networks, to networks used both for the delivery and generation of energy.

This thesis presents analytical methods to facilitate integration of DG into the existing grid distribution systems. The method is applied to distribution system for determining the optimal location and size of DG with respect to the technical constraints on DG such as, voltage sensitivity and losses both at the same time to use existing distribution network in an optimal manner. The method is implemented and tested on Adama town distribution network.

Results of optimal DG size and place with respect to voltage sensitivity and loss reduction are presented demonstrating the best places and the size of DG for the Adama distribution network to make the system highly reliable. It is shown that bus 5 and bus 1 have the least voltage sensitivity index **0.223146** and **0.56570** respectively and are selected as the best places to install DG. To determine the size of DG to be installed minimum loss reduction factor is used and the maximum DG size for bus 1 is found to be **4MW** and for bus 5 is found to be **8MW**. Finally for Adama distribution system reliability before DG integration and after DG integration was compared and resulted in reliability improvement of **62.428%**.

Key words: DG optimal location, DG optimal size, distributed generation, objective function, distribution system reliability, technical constraints, loss reduction.

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List of Abbreviations

ADS: Adama distribution system

ANSI: American National Standards Institute

ASAI: Average Service Availability Index

ASUI: Average Service Unavailability Index

CAIDI: Customer Average Interruption Duration Index

CAIFI: Customer Average Interruption Frequency Index

CHP: Combined heat power

CIREN: The International Conference on Electricity Distribution

DER: Distributed energy resources

DFIG: Doubly fed induction generators

DG: Distributed generation

DNO: Distribution Network Operator

ENS: Energy Not Supplied

GIS: Geographic information systems

HV: High Voltage

IEEE: Institute of Electrical and Electronics Engineers

LDC: Line drop compensator

LTC: Load Tap changing transformers

LV: Low Voltage

PF: Power Factor

PL: power loss

PV: Photovoltaic

RMS: Root mean square value

SAIDI: System Average Interruption Duration Index

SAIFI: System Average Interruption Frequency Index

SLG: Single line-to-ground

T&D: Transmission and Distribution

VSI: Voltage Sensitivity Index

1 Introduction

1.1 Background

Electric power generation once began with nearby generators regularly associated with steam engines. At that time electricity distribution networks were mainly covering small areas which were equipped with their own generators. Since that time electricity networks have become more and more interconnected and today electricity networks form wide area transmission networks over thousands of kilometers. While the networks became larger and more widespread, the electricity power consumption was increasing and large power plants were built to supply the residential, industrial and other loads with electrical power. The large power plants are in most cases coal or gas fired thermal power plants or nuclear power plants. In areas with convenient conditions like Ethiopia large scale hydro power plants are quite usual. Common for all of the large scale power plants is the fact that they are connected to high voltage (HV) transmission networks and the power is then transferred through the transmission network to the distribution network and finally to the customers.

The generation of electricity from gas and coal fired power plants is discharging carbon dioxide and has thus been pointed out as one of the key topics when discussing CO₂ emission reductions. As nuclear power plants are controversial due to the operation security and their nuclear wastes. Electricity from hydro power plants is renewable but new units can only be built at suitable locations. To achieve the climate and energy targets electricity from renewable sources is valuable. Wind power (WP) has been successful for several years but also photovoltaic (PV) and biomass-fired combined heat power (CHP) have been increasing a lot in many countries during recent years.

In contrast to the conventional large scale power plants with a generation capacity of some hundreds up to more than 1000MW per unit, these new generation units driven by renewable sources are often small scale. Thus they are usually dispersed and connected to the distribution network, where also customers are connected. Generation units located in

total network load. In such cases it is often possible simply to consider the DG units as negative loads. However, the penetration of DG is increasing and the power flow is reversed at least during some periods, new challenges such as voltage rise along distribution feeders appear.

In passive distribution networks, as it still is the common type, there is no coordination between the actual network situation and the devices connected to it. Such networks have to be designed to tackle worst cases as maximum load/minimum generation and minimum load/maximum generation by dimensioning the lines and other equipment to fulfill the requirements. Active distribution systems in contrast assume at least some kind of feedback or participation from the devices connected to the distribution network.

The electricity marketplace is undergoing a tremendous transformation as it moves towards a more competitive environment. The 'growing pains' of this transformation price instability, an ageing infrastructure, changing regulatory environments are causing both energy users and electric utilities to take another look at the benefits of distributed generation(DG).[2]

The increasing penetration of DG is changing the role of distribution systems. What were originally passive networks purely for the delivery of electricity to the consumer are now networks that are being utilized for the harvesting of energy from a numerous distributed energy resources. The increased proliferation of these distributed generators has led to changes in the characteristics of the network, with more variable and bidirectional active and reactive power flows. These generators are altering the technical characteristics of the networks, and pushing them to operate closer to their limits of safe and reliable operation. As a result, the need for distribution networks to operate at their maximum capacity is being felt particularly with DG

1.2 Problem Formulations

These days, the electric power consumption is increasing quickly and one of the basic responsibilities of power engineers is to generate power from renewable energy sources to beat this increment in the energy demand and at the same time decrease environmental effect of power generation. The use of renewable sources of energy has reached greater

importance as it promotes sustainable living and with some exceptions (such as biomass combustion) does not contain contaminants. Renewable sources can be used in either small-scale applications away from the large sized generation plants or in large-scale applications in locations where the resource is abundant and large conversion systems are used

Distributed generation and its integration with the power distribution network is one way of meeting the increases in this energy demand. When connecting distributed generation to distribution network the amount of DG penetration and optimum DG placement must be determined to make the existing system reliable, with good power quality and effective protection system as these are the issues related with distributed generation

This thesis addresses the integration of distributed generation with the distribution system to improve the existing system reliability by finding a method for Optimal DG placement and size.

1.3 Thesis objective

1.3.1 Main objective

The main objective of this thesis is to study and implement integration of DG to an electric power distribution system so that it can deliver adequate electric supply to its customer and improve distribution system reliability.

1.3.2 Specific objective

The specific objectives of this thesis are:

- ✓ Study the technical constraints and factors which are impacted by the amount of DG that is connected
- ✓ To determine the optimal location for placing distributed generation in network for a better power quality and reliability of distribution systems.
- ✓ To determine the maximum possible DG integration with respect to the given constraints
- ✓ To study distribution reliability improvement by using DG

1.4 Motivations for Distributed Generation

DG motivation is found by customers and energy producers as they all find benefits in DG applications. The maintenance of transmission and distribution (T&D) systems is a tough and expensive task for utilities; improvements are regularly necessary to keep up with energy consumption growth. DG can offer delay of these prices in some cases. By employing DG at the distribution level where there is significant growth, else needed improvements of the equipment upstream can be avoided while the energy losses related with T&D can be reduced. Studies can reveal that of the end-user price that customers pay for electricity, it's been found that approximately 30% of those costs are attributed to T&D costs [3], [4]. These costs can potentially be decreased or eliminated by on-site energy production of DG.

Demands for higher *reliability* of electric supply in our country are constantly increasing, especially for industry applications as we are transforming to industrial based economy such as chemicals, refining, paper, metals, telecommunications, and the like. This will create an opportunity for our utilities to invest in DG for the purpose of increasing overall reliability.

Environmental concerns have led to the development of rules that encourage the implementation of DG, though sometimes indirectly. Most renewable energy sources offer themselves, by nature, to DG rather than centralized plant applications.

Therefore all the above points are the motivations for the integration of DG into the existing distribution system

1.5 Thesis Outline

The thesis is structured as follows;

Chapter 1 presents the background, problem statements, objectives and motivation for DG integration.

Chapter 2 gives some background and explanation of distributed generation (DG) and difference between tradition centralized power generation concept and DG. Criteria for

classification of DG and, their application and different technologies used for DG are presented. Finally it presents some selected publications on DG.

Chapter 3 presents Distributed Generation Network Issues. When integrating DG to distribution network there must be some constraints such as voltage rise, short circuit level, losses and the likes which should be considered .This will be briefly discussed under this chapter.

Chapter 4 presents the concept of power quality and reliability. Under this chapter the different distribution system reliability indices and how DG will improve distribution system reliability are discussed

Chapter 5 presents the methods used for finding optimal location and size of DG in the distribution system. The optimal placement and size of DG will be presented with the case study of Adama distribution system. Distribution system reliability improvement using DG also presented by calculating the reliability indices with and without DG integration.

Chapter 6 presents conclusions, recommendation and future works

2 Literature survey on distributed generation

2.1 Distributed Generation Background

Generally, the term Distributed Generation refers to any small scale electric power production technology that is integrated within distribution systems, near to the point of utilization. Distributed generators are connected to the medium or low voltage grid. They are not centrally planned and they are typically smaller than 30 MW (DTI 2001) [5].

The concept of DG contrasts with the traditional centralized power generation concept, where the electricity is generated in large power stations and is transmitted to the end users through transmission and distributions lines (see figure 2.1). While central power systems remain critical to the global energy supply, their flexibility to adjust to changing energy needs is limited. Central power is composed of large capital-intensive plants and a transmission and distribution (T&D) grid to disperse electricity

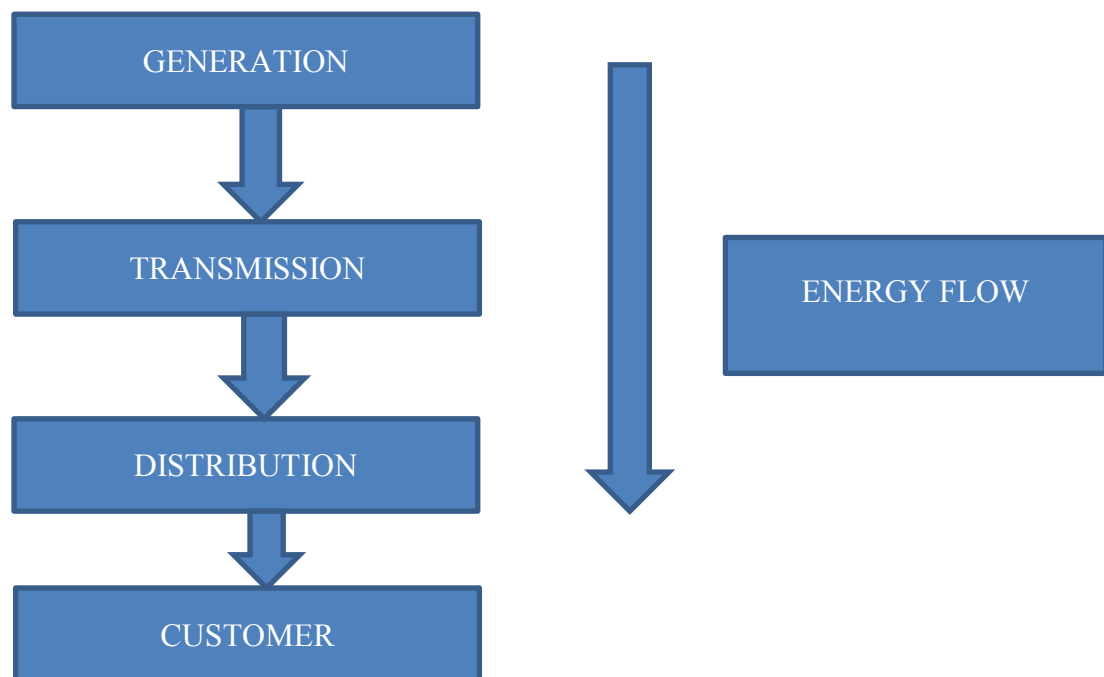


Figure 2-1. Power flow before the integration of distributed generation

A distributed electricity system is one in which small and micro generators are connected directly to factories, offices, households, and to lower voltage distribution networks.

Electricity not required by the directly connected consumers is fed into the active distribution network to meet demand elsewhere. Energy storage systems may be used to store any surplus generation. Such a distributed electricity system is represented in figure 2-2 below.

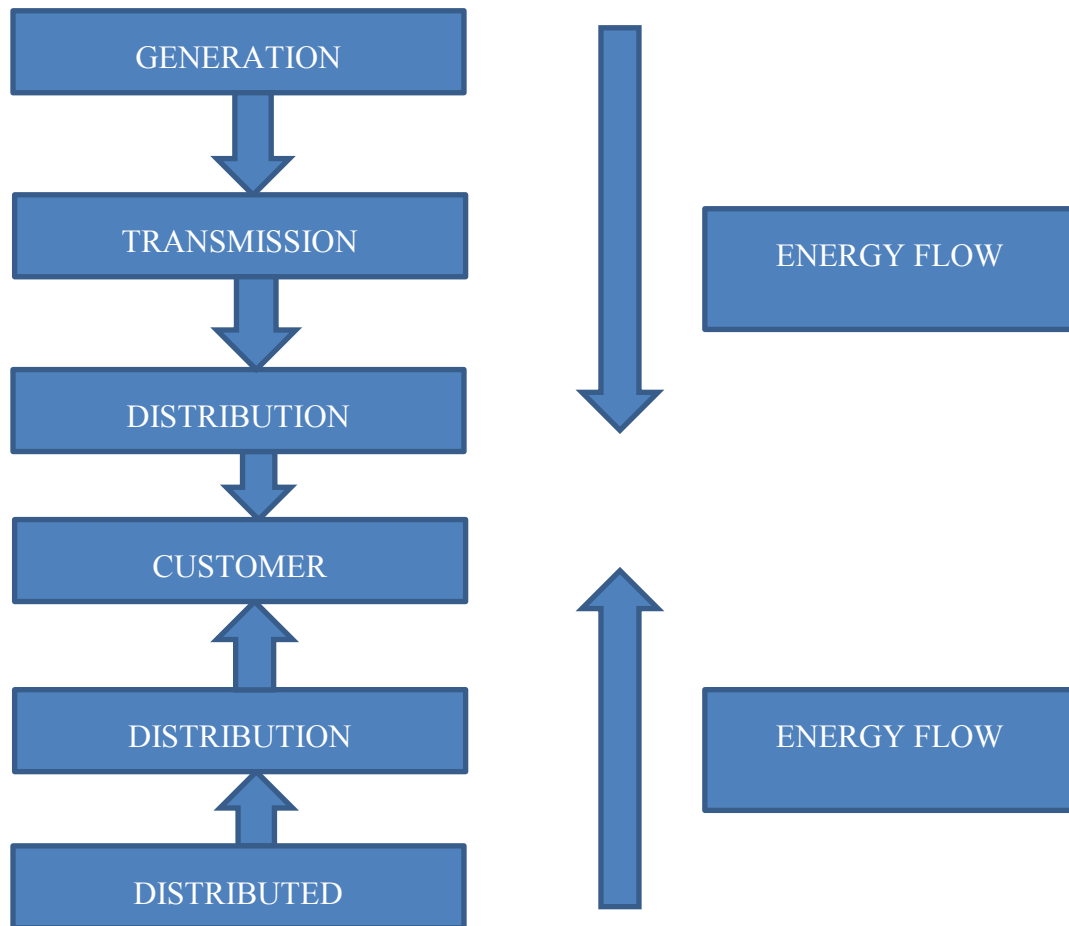


Figure 2-2- Power flow after the integration of distributed generation

Distributed generation systems offer clean, efficient, reliable, and flexible on-site power alternatives. Both DG and central power choices need significant investments of time and money to raise capacity but, distributed generation complements central power by

1. Providing in many cases a relatively low capital cost response to incremental increases in power demand,
2. Avoiding T&D capacity upgrades by locating power where it is most needed, and
3. Having the flexibility to put power back into the grid at user sites.

Major technological improvements through decades of serious research have produced serious improvements in the economic, operational, and environmental performance of small, modular power generation options. Forecasts predict a total 520GW from newly installed DG around the globe by 2030. [6]

2.2 Criteria for classification of power generation as DG

The criteria generally used to decide what generation should fall under the classification of DG are size, location, voltage level, type, and use/application.

Size

Those who qualify DG by size in part, or in whole normally set a cut-off of about 50MW-100MW as the maximum size of generation that could qualify as DG.

Location

The location of generation is employed as a standard because of the fact that DG is regularly thought to be generation that is utilized directly by end-users without transmission line being essential. In this way, the closeness of the generation to the loads it supplies is some of the time used to classify DG.

Voltage Level

Voltage level is also used to characterize DG, where generation at or beneath the maximum distribution level voltage is typically the maximum voltage level of DG. This is a mainly poor classifier since there is often overlap between transmission voltage levels and distribution voltage levels. Moreover, different nations utilize essentially different levels of voltage for distribution purposes.

Type of Generator

The nature of generation, or the fuel source, is sometimes used to describe DG, but this is usually done in a case where DG is meant to refer more specifically to renewable/alternative sources of generation.

Use / Application

The proposed use or application is used to classify DG because it is frequently employed directly at the load for direct consumption. This varies from the location criterion because the question can be raised as to whether or not a generator located directly adjacent to a load qualifies as DG when it is owned and operated by the utility for grid support [7]. It should be mentioned that in some cases, energy storage units are considered DG. This could include capacitors and batteries, which are not actually generators [8].

2.3 Distributed Generation Applications and Technologies

2.3.1 DG Applications

Dispersed generation (DG) is presently being utilized to give some or the greater part of the power needs. There are a wide range of potential applications for DG technologies.

For instance, some customers use DG to decrease demand charges imposed by their electric utility, while others use it to deliver primary power or reduce environmental emissions. DG can also be used by electric utilities to improve their distribution systems. Many other applications for DG solutions exist. The following is a list of those of potential interest to electric utilities and their customers.

Continuous Power

In this application, the DG technology is run at least 6,000 hours a year to let a facility to generate some or all of its power on a relatively continuous basis. Essential DG characteristics for continuous power include:

- ✓ High electric efficiency
- ✓ Low variable maintenance costs
- ✓ Low emissions

At present, DG is being consumed most often in a continuous power capacity for industrial applications such as food manufacturing, plastics, rubber, metals and chemical production.

Combined Heat and Power (CHP)

Also referred to as cogeneration, this DG technology is run at least 6,000 hours per year to permit a facility to produce some or all of its power. A portion of the DG waste heat is used for water heating, space heating, steam generation or other thermal needs. Important DG characteristics for combined heat and power include:

- ✓ High useable thermal output (leading to high overall efficiency)
- ✓ Low variable maintenance costs
- ✓ Low emissions

CHP characteristics are similar to those of Continuous Power, and thus the two applications have almost identical customer profiles, though the high thermal demand here is not necessary for Continuous Power applications.

Peaking Power

In a peaking power application, DG is operated between 200-3000 hours per year to reduce overall electricity costs. Units can be operated to reduce the utility's demand charges. Important DG characteristics for peaking power include:

- ✓ Low installed cost
- ✓ Quick startup
- ✓ Low fixed maintenance costs

Green Power

Important DG characteristics for green power applications include:

- ✓ Low emissions
- ✓ High efficiency
- ✓ Low variable maintenance costs

Premium Power

DG is used to deliver electricity service at a higher level of reliability and/or power quality than typically available from the grid. Customers typically demand uninterrupted power for a variety of applications

Emergency Power System

This is an independent system that automatically provides electricity within a specified time frame to replace the normal source if it fails. The system is used to power critical devices whose failure would result in property damage and/or threatened health and safety.

Standby Power System

This independent system provides electricity to replace the normal source if it fails and thus allows the customer's entire facility to continue to operate satisfactorily.

True Premium Power System

Customers who request continuous power, free of all power quality issues utilize this system. Power of this quality is not available directly from the grid. DG technology can be used as the primary power source and the grid can be used as a backup. This technology is used by mission critical systems like airlines, banks, insurance companies, communications stations and hospitals

Important DG characteristics for premium power (emergency and standby) include:

- ✓ Quick startup,
- ✓ Low installed cost
- ✓ Low fixed maintenance costs

Transmission and Distribution Delay

Sometimes, placing DG units in strategic locations can help to postpone the purchase of new transmission or distribution systems and equipment such as distribution lines and substations. Important DG characteristics for transmission and distribution deferral include:

- ✓ Low installed cost
- ✓ Low fixed maintenance costs

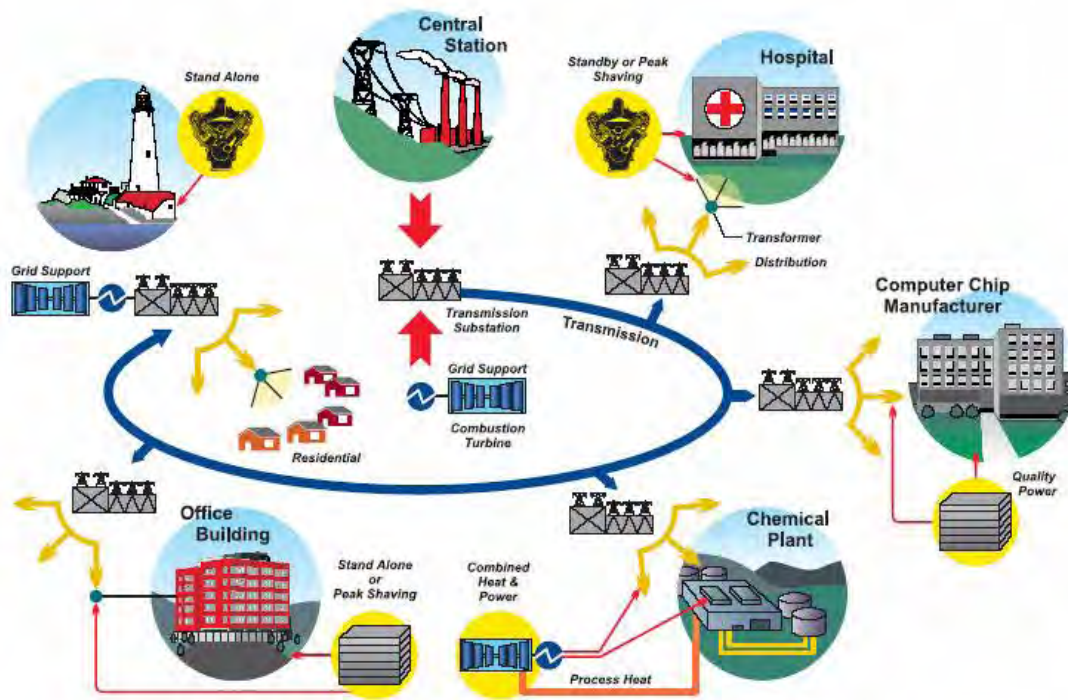


Figure 2-3- Summary of DG applications [4]

2.3.2 Types of Distributed Generation and Technologies

DG can be categorized into two major groups, inverter based DG and rotating machine DG. Normally, inverters are used in DG systems after the generation process, as the generated voltage may be in DC or AC form, but it is required to be changed to the nominal voltage and frequency. Therefore, it has to be converted first to DC and then back to AC with the nominal parameters through the rectifier [9].

In this section, some of the DG technologies, which are available at the present: photovoltaic systems, wind turbines, fuel cells, micro turbines, synchronous and induction generators are introduced.

2.3.2.1 Photovoltaic Systems

- ✓ Converts the light received from the sun into electric energy.
- ✓ These systems are environmental friendly without any kind of emission.
- ✓ Easy to use, simple designs and it does not require any other fuel than solar light.

- ✓ On the other hand, they need large spaces and the initial cost is high.
- ✓ PV systems generate DC voltage then transferred to AC with the aid of inverters

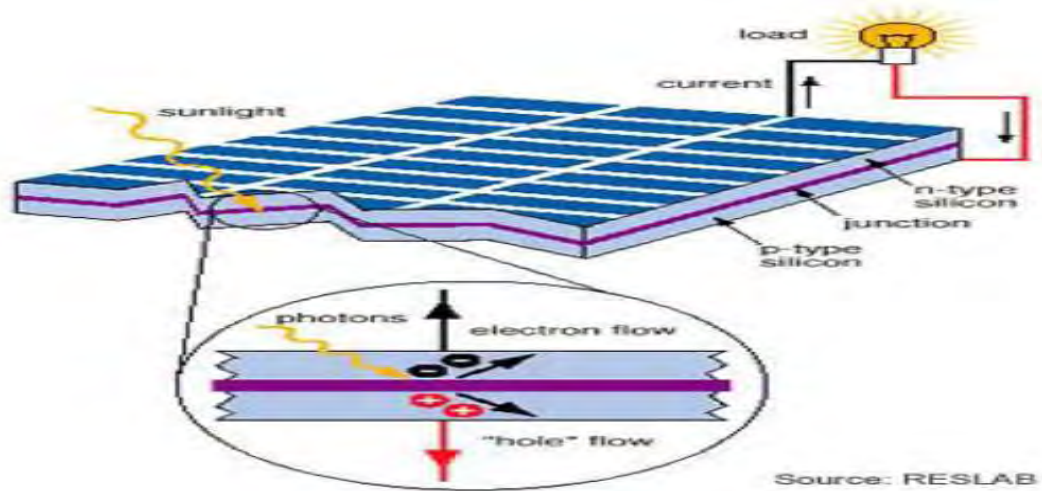


Figure 2-4- Schematic diagram of a photovoltaic system [10]

2.3.2.2 Fuel Cells

- Fuel cells are not only very efficient but also have very low emission levels.
- It supplies electricity by combining hydrogen and oxygen electrochemically without combustion.
- The final product is pure water; the electrochemical reaction generates electricity and heat without a flame ("cold combustion").
- A single cell provides less than one volt, so a series of fuel cells are normally "stacked" one on another to increase the power output.

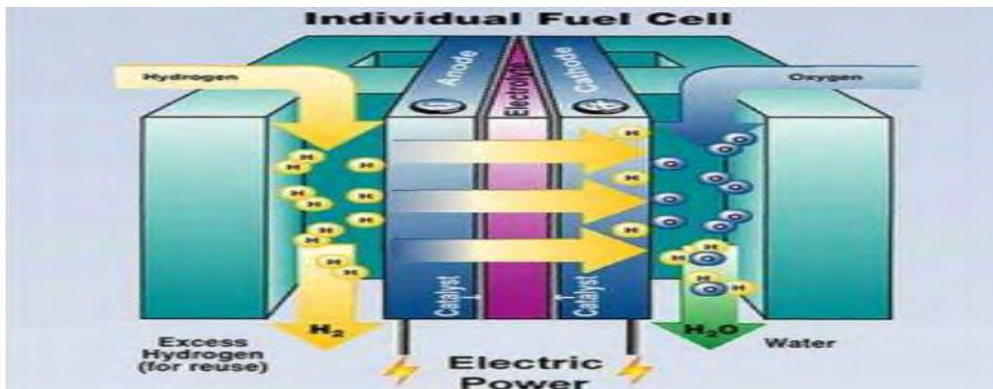


Figure 2-5- Schematic diagram of a fuel cell [11]

2.3.2.3 Wind Turbines

- Wind turbines transform wind energy into electricity.
- The wind is a highly variable source, which cannot be stored, thus, it must be handled according to this characteristic.
- In the most common system, the generator system gives an AC output voltage that is dependent on the wind speed.
- As wind speed is variable, the voltage generated has to be transferred to DC and back again to AC with the aid of inverters.
- However, fixed speed wind turbines are directly connected to grid [12]

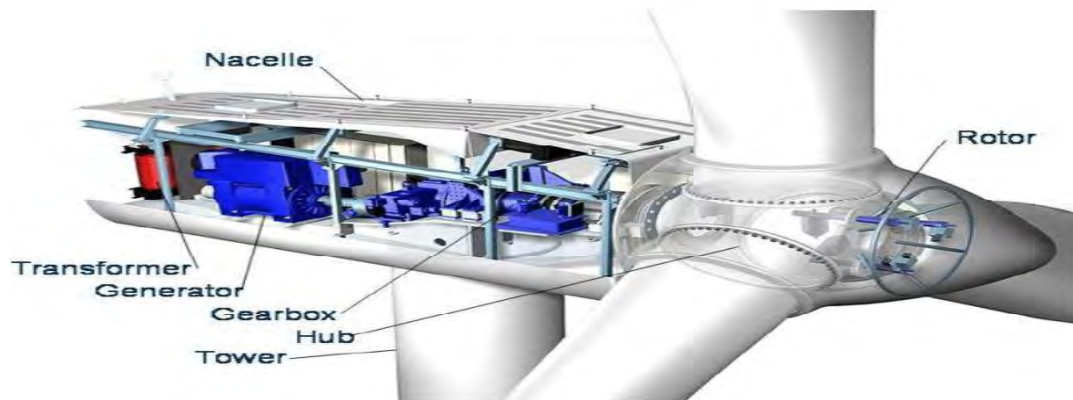


Figure 2-6- Schematic operation diagram of a wind turbine [13]

2.3.2.4 Micro-Turbines

- A micro-turbine is a mechanism that uses the flow of a gas, to convert thermal energy into mechanical energy.
- The output voltage from micro-turbines cannot be connected directly to the power grid or utility, it has to be transferred to DC and then converted back to AC in order to have the nominal voltage and frequency of the utility.
- The main advantage of micro-turbines is the clean operation with low emissions produced and good efficiency.
- Its disadvantages are the high maintenance cost and the lack of experience in this field.

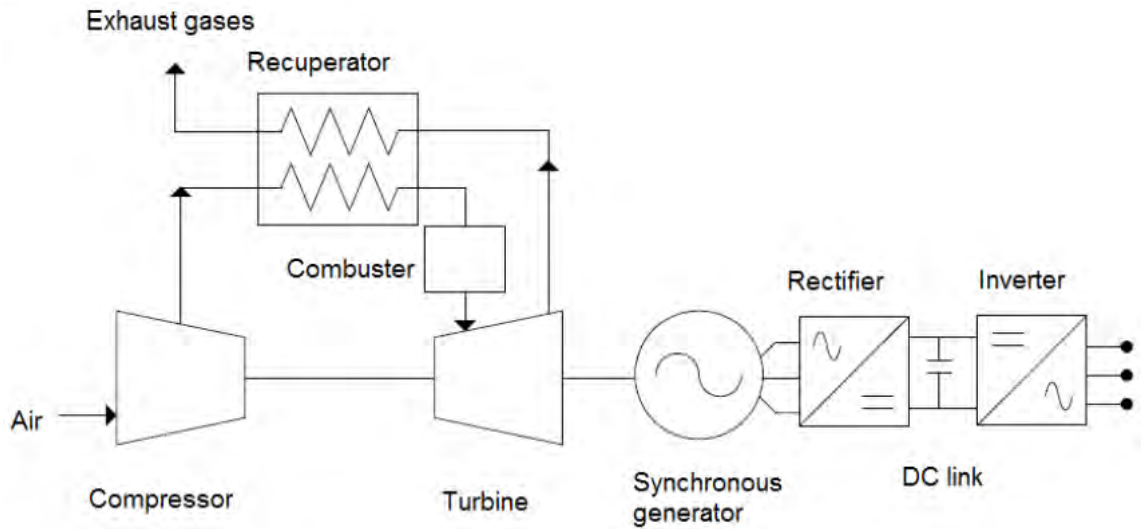


Figure 2-7- Schematic diagram of a micro-turbine [14]

2.3.2.5 Industrial combustion turbines

- A mature technology, combustion turbines range from 1 MW to over 5 MW.
- They have low capital cost, low emission levels, but also usually low electric efficiency ratings.
- Industrial combustion turbines are being used primarily for peaking power and in cogeneration applications.

2.3.2.6 Induction and Synchronous Generators

- Induction and synchronous generators are electrical machines which convert mechanical energy into electrical energy then dispatched to the network or loads.
- The synchronous generator operates at a specific synchronous speed and hence is a constant-speed generator.
- In contrast with the induction generator, whose operation involves a lagging power factor, the synchronous generator has variable power factor characteristic and therefore is suitable for power factor correction applications.

2.3.2.7 Reciprocating engines

- This DG technology was developed more than a century ago, and is still widely utilized in a broad array of applications.

- Reciprocating engines are being used primarily for backup power, peaking power, and in cogeneration applications.

Certain type of DGs like photovoltaic will produce real power only. Other types of DG will supply real power and in turn will absorb reactive power. In the case of the wind turbines, induction generator is used to produce real power and the reactive power will be consumed in the process. To find the optimal DG size and location at bus i for both cases we need different control mechanism for minimum loss. Therefore to simplify our study and analysis from the above listed DG technologies for this thesis wind turbine is used. The site under consideration is also suitable for wind power generation with average wind speed of (8-9 m/s) [15] and simplifies the study.

2.4 Some selected publications

A number of publications have been reviewed at optimizing the placement and sizing of DG based on various criteria. Selections of the more relevant publications are given here.

In [16] the authors apply an optimal power flow (OPF) technique to maximize DG capacity with respect to voltage and thermal constraints. Short circuit levels, short circuit ratio, equipment ratings and losses are not considered. In [17] a method is presented utilizing OPF for the allocation of generation capacity, which includes a detailed fault level constraint. Short circuit constraints are not considered and the focus of the objective function is on optimal investment rather than maximizing renewable energy. In [18] a planning process that considers DG as well as more conventional options is presented. DG investment is considered under a number of load growth scenarios, with its benefit found to vary between each scenario. In [19] a multi objective planning strategy is presented using a genetic algorithm to identify the best compromise DG sizing and siting. In [20] the amount of losses experienced with increasing penetrations of DG sources is examined. The authors propose a method which places DG at the optimal place along feeders and within networked systems with respect to losses. The allocation of losses to distributed generators in the network has been addressed in [20] Previous work has attempted to quantify the net benefits of DG [21] where a number of benefits such as reduced losses and voltage profile were assessed. A number of the operational issues

surrounding DG have also been addressed in the literature. In [22] methods to estimate the amount of wind power that could be installed in areas with congestion problems are presented. The methods are applied to the Swedish transmission network and the cost of the spilled energy is determined.

Other work has focused on the reliability worth of DG [23] and the consideration of an optimal operating strategy for DG on an hourly basis. In [24] a probabilistic reliability model is presented to determine the impact of DG for use in distribution planning studies. In [25], the impact of DG on reliability and power quality is measured. Work has been done evaluating the contribution of wind generation, in particular, to reliability

It is obvious from the selection of publications mentioned above that a considerable body of work has been carried out into the integration of DG.

3 Distributed Generation Network Issues

3.1 General Planning & Operational Issues

The addition of DG modifies the characteristics of the distribution system. A number of technical restrictions and issues arise which are impacted by the amount of DG that is connected. These issues are:

- ✓ Equipment Ratings
- ✓ Short Circuit Level
- ✓ Short Circuit Ratio
- ✓ Voltage Rise
- ✓ Losses

3.1.1 Equipment Ratings

The rated current of the lines and the transformer rating must not be exceeded.

Capacity of Transformer

The extent of generation connected minus the lowest load must not exceed the transformer rating at the higher voltage. If there is some existing generation then this must be subtracted from the total. The result is the remaining capacity available below that station. In the case of two parallel transformers, the capacity is taken as the rating of the smaller transformer plus the lowest load. The constraint is expressed formally as in Equation (3.1)

$$PTx < PTrafoCap \dots\dots\dots 3.1$$

Where PTx refers to power flow through the transmission substation transformer and PTrafoCap refers to the rating of that transformer.

Thermal Constraint

This is a separate constraint; simply the rated current of the lines could not be exceeded. It is given by Equation (3.2).

$$I_i < I_i^{Rated} \quad \forall N \dots\dots\dots 3.2$$

Where I_i is the current flowing from generator i to bus i and I_i^{Rated} is the maximum rated current for the line between each generator and its corresponding bus. Under standard voltage and power factor conditions the rated current of the line can be translated directly into a rated active power for that line.

3.1.2 Short Circuit Level (SCL)

The size of the transient voltage drop experienced at the buses in a network is a sign of strength of the system. In this way the SCL is a measure of the strength or robustness of a system [26]. The SCL of a system denotes to the current that results when there is a fault on the system

A maximum short circuit rating for all equipment is laid down in IEEE distribution codes

A short circuit calculation is carried out to ensure that this constraint is not exceeded as the level of installed capacity increases.

The short circuit level (SCL) is highest at the transmission system bus. Buses close to this bus may find their capacity limited as a result. The constraint is given by Equation (3.3).

$$SCL_{TX} < SCL_{Rated} \dots\dots\dots 3.3$$

Where SCL_{TX} is the short circuit level at the transmission substation busbar and SCL_{Rated} is the highest current that switchgear can safely break under fault conditions. The contribution of increasing levels of generation at each bus to SCL_{TX} is determined by short circuit analysis. The SCL contributions of generation at each bus are combined and formalized into an algebraic equation as shown in Equation (3.4).

$$\sum_{j=1}^N \delta_j Tx PDG_j + \alpha Tx \leq SCL_{Rated} \dots\dots\dots 3.4$$

Where $\delta_j Tx$ is the dependency of the SCL at the transmission station to power injections at bus j , i.e. the slope of the SCL vs. power injection characteristic of the j^{th} bus.

PDG_j is the power injection at the j th bus;

αT_x is the initial SCL at the transmission bus with no generation present.

Equation (3.4) is a very accurate model of the short circuit characteristics when an intelligent choice of the range for calculation of the slopes is made.

3.1.3 Short Circuit Ratio (SCR)

The short circuit ratio (SCR) is the ratio of generator power PDG (MW) at each bus to the short circuit level at each bus SCL bus (MVA) [27]. It provides a clue of the voltage fall experienced near the generation in the event of a feeder outage.

The connection of induction generators to high impedance circuits may lead to voltage instability problems if the SCR is not kept within acceptable limits [28]. If the short circuit ratio is small enough, a transient voltage dip occurring will be limited and the system will remain stable. The contribution of other generators to the SCL is considered as it may be significant depending on the proximity of the bus. The phase angle at the busbar is omitted as an extra margin of safety. It could be included and the allowable ratio set to a lower value such as 6%. A value of 10% is largely in line with values used by other utilities and is in line with the value recommended in the European standard EN50160 [29] The ratio itself is shown in Equation 3.5

$$\frac{PDG_i}{SCL_i \cos\phi} \times 100 \leq 10\% \forall N \dots\dots\dots 3.5$$

Where SCL_i refers to the short circuit level at the i th bus and $\cos\phi$ is the power factor of the generator. A base value for the short circuit level at the i th bus is calculated with no generation present on the network, α_i . The contribution, if any, of generation at other buses to this level is then calculated allowing the short circuit characteristic of each bus to be formulated into an algebraic equation. The SCL at the i th bus is given by Equation (3.6).

$$SCL = \alpha_i + \sum_{j=1}^n \delta_j PDG_j \neq j, i \forall N \dots\dots\dots 3.6$$

Substituting equation 3.6 in to 3.5

$$PDGi - 0.1\cos\phi \sum_{j=1}^N \delta_j i PDGj \leq 0.1\cos(\phi)\alpha i \dots\dots\dots 3.7$$

3.1.4 Voltage Rise

If DG is connected to a network unit, it will change the active and reactive power flows and therefore change the voltage dropped across the lines. It has been shown that DG leads to a significant voltage rise at the end of the long, high impedance lines [30]. A rise in voltage occurs if there is low demand and high generation, which leads to a large amount of power flow along lightly loaded lines with high impedance

From the circuit shown below the voltage at the generator is given by Equation (3.8).

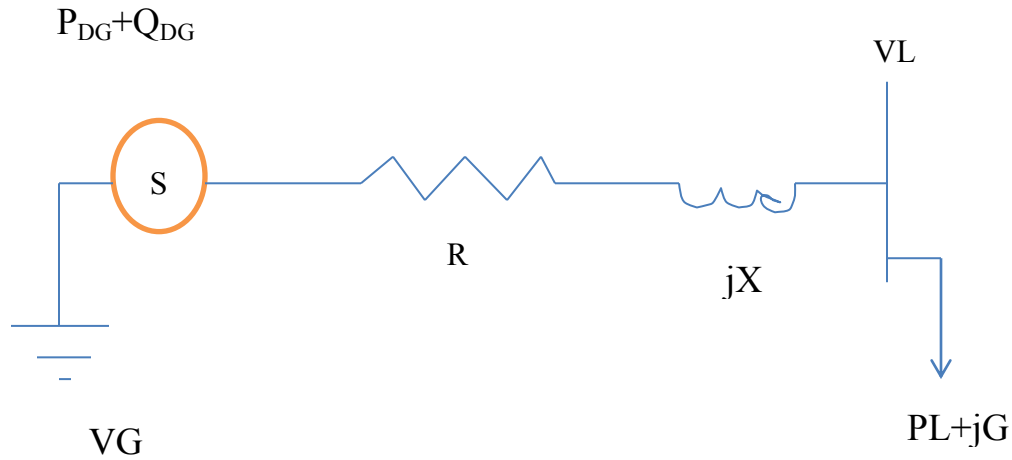


Figure 3-1-Voltage rise effect

$$V_G = V_L + \frac{R P_L + X Q_L}{V_L} + j \frac{X P_L - R Q_L}{V_L} \dots\dots\dots 3.8$$

Where $Z=R+jX$ is the impedance of the line, P_L and Q_L are active and reactive power at the bus and V_G and V_L are the voltages at the generator and bus respectively. Thus it can be seen that the generator voltage will be the load/bus voltage plus some value related to the impedance of the line and the power flows along that line. It is evident that the larger the impedance and power flow the larger the voltage rise. The increased active power flows on the distribution network have a large impact on the voltage level because the

resistive elements of the lines on distribution networks are higher than other lines. The voltage must be kept within standard limits at each bus as given by Equation (3.9).

$$V_{\min i} < V_i < V_{\max i} \forall N \dots\dots\dots 3.9$$

Where $V_{\min i}$ & $V_{\max i}$ refer to the minimum and maximum voltage limits at the i th bus. The relationship between voltage and power injections at each bus is determined. As megawatts are added at each bus the voltage rises. Increasing levels of generation are added incrementally at each bus in turn and load flow analysis is carried out to determine a voltage vs active power characteristic for each bus. Next the interdependence of the bus voltage levels is examined. Once again increasing levels of generation are added incrementally at each bus, but now the voltage level at every other bus is examined. Thus characteristics are determined for voltage levels at each bus due to generation at all other buses. By combination of these characteristics the voltage constraint may be formalized into algebraic equations for each bus as shown in Equation (3.10).

$$\sum_{j=1}^N \mu_{ji} PDG_j + \beta_i \leq V_{\max j}, i \forall N \dots\dots\dots 3.10$$

Where μ_i is the dependency of the voltage level at bus i on power injections at bus i , i.e. the slope of the voltage vs. power injection characteristic of the i^{th} bus. β_i refers to the initial voltage level at the i^{th} bus with no generation, μ_{ji} refers to the dependency of the voltage level at bus i on power injections at bus j . This analysis is carried out under minimum load conditions as this is the worst case scenario for voltage rise.

3.1.5 Losses

Losses are significant consideration when designing and planning the distribution system. Losses are unavoidable on any network; however, the amount can differ greatly depending on the design of the network. With the introduction of distributed generation, the network is being used in a different way with more variable and bidirectional power flows. The level of losses is closely linked to the power flows. Losses are function of the square of the current, i.e. a doubling in current results in losses being quadrupled.

Therefore the allocation of DG and the altered power flows that result may have a significant impact on losses and may provide an opportunity to improve them.

3.2 DG Interconnection

The connection of DG with the network is a complicated procedure that involves the realization of a DG application. The DG operation is usually referred to as synchronized or parallel operation. In synchronized configuration DG is connected to the network the same time that it's producing power and in the case that the load is met any excess energy is also transmitted to that.

The parallel DG operation is the most complicated in contrast with a stand-alone DG application. The complexity of DG operation generally depends on the level of interaction with the existing network.

- Isolated, stand-alone source (fig.3-2):

In this case the load is met by DG only with no network connection

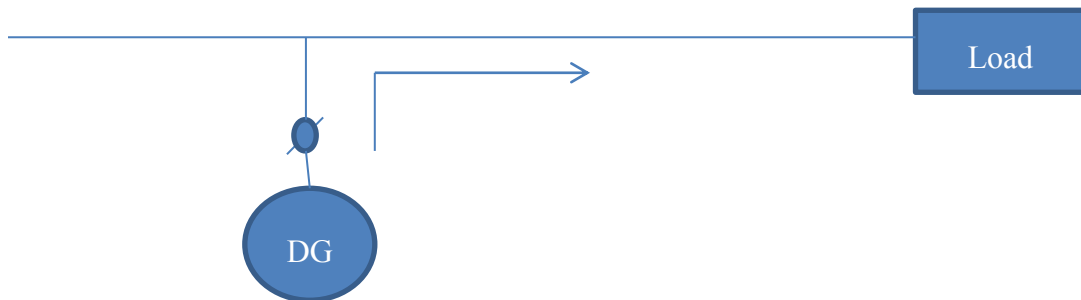


Figure 3-2- Isolated, standalone source

- Isolated system with automatic transfer (fig.3-3):

DG provides power in Load 2. The network covers Load 1 and Load 2 when needed. DG does not work in parallel except for a few sec.

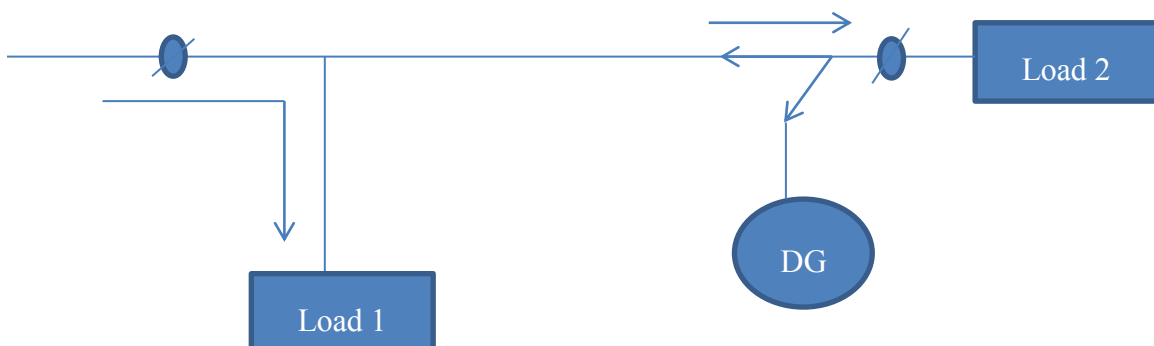


Figure 3-3-Isolated system, with automatic transfer

- DG connected to the network with no power export (fig.3-4):

DG operates in parallel to the grid by transmitting power to one or more loads without sending any excess energy to the grid

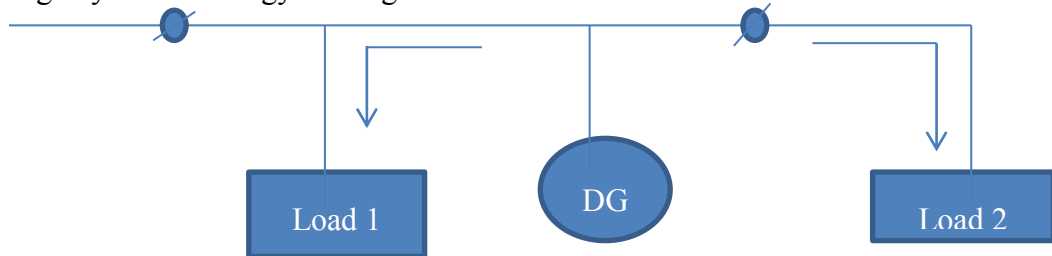


Figure 3-4- DG connected to the network with no power export

- DG grid interconnected with power export (fig.3-5):

DG operates in parallel to the grid and there exists the option to supply any excess power to the grid.

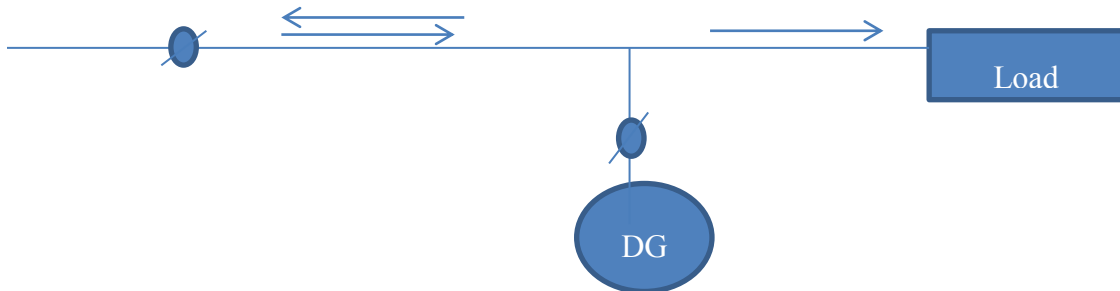


Figure 3-5- DG grid interconnected with power export

- Grid interconnected with power export- utility side (fig.3-6):

The system supplies the base load, standby power, and peak load. DG operates in parallel

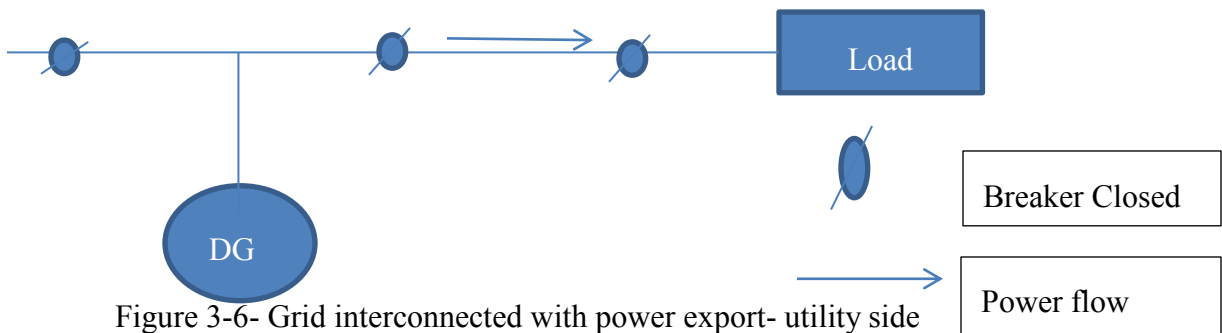


Figure 3-6- Grid interconnected with power export- utility side

4 Power Quality and Reliability

4.1 The Concept of Power Quality

The definition of power quality given in the IEEE dictionary originates in IEEE Std 1100 [31]: *Power quality is the concept of powering and grounding sensitive equipment in a manner that is suitable to the operation of that equipment.*

Despite this definition the term power quality is clearly used in a more generic way.

Within the industry, alternate definitions or interpretations of power quality have been used, reflecting different points of view. Therefore, this definition might not be exclusive, pending development of a broader consensus.

A point of view of an equipment designer or manufacturer might be that power quality is *a perfect sinusoidal wave, with no variations in the voltage, and no noise present on the grounding system.*

A point of view of an electrical utility engineer might be that power quality is *simply voltage availability or outage minutes.*

Finally, a point of view of an end-user is that power quality or “quality power” is *simply the power that works for whatever equipment the end-user is applying.*

While each hypothetical point of view has a clear difference, it is clear that none is properly focused.

4.2 Overview of Power Quality Phenomena

4.2.1 Overvoltage

When used to describe a specific type of long duration variation, refers to a measured voltage having a value greater than the nominal voltage for a period of time greater than 1 min. typical values are 1.1 to 1.2 p.u [32]

Overvoltage can be the result of load switching or poor system voltage regulation capabilities or controls. Figure 4-1 shows a typical overvoltage waveform.

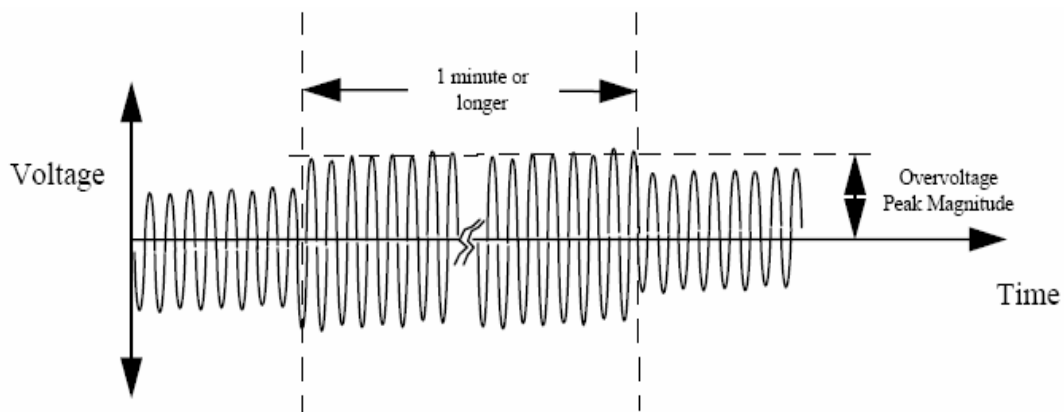


Figure 4-1-Typical overvoltage waveform [33]

4.2.2 Undervoltage

When used to describe a specific type of long duration variation, a measured voltage having a value less than the nominal voltage for a period of time greater than 1 minute. Typical values are 0.8 - 0.9 p.u. [34].

Under voltages are the results of the events which are the reverse of the events that cause overvoltage. Overloaded circuits can also result in undervoltages.

4.2.3 Sag

Sag is a decrease to between 0.1 and 0.9 p.u. in rms voltage or current at the power frequency for durations of 0.5 cycles to 1 min. typical values are 0.1 to 0.9 p.u. [34] Voltage sags are usually associated with system faults but can also be caused by switching of heavy loads or starting of large motors.

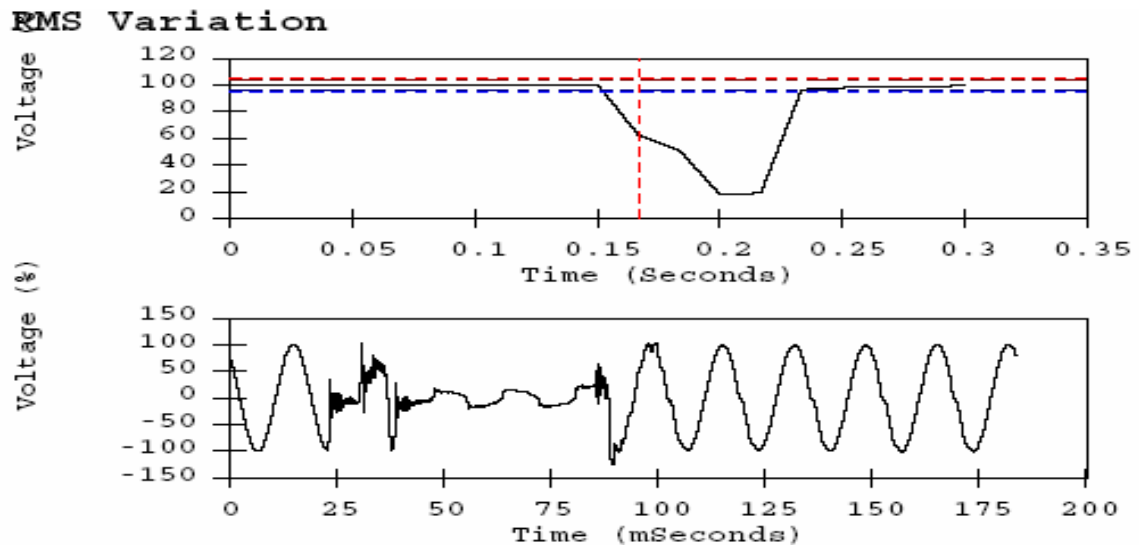


Figure 4-2- Instantaneous voltage sag caused by a SLG fault [34]

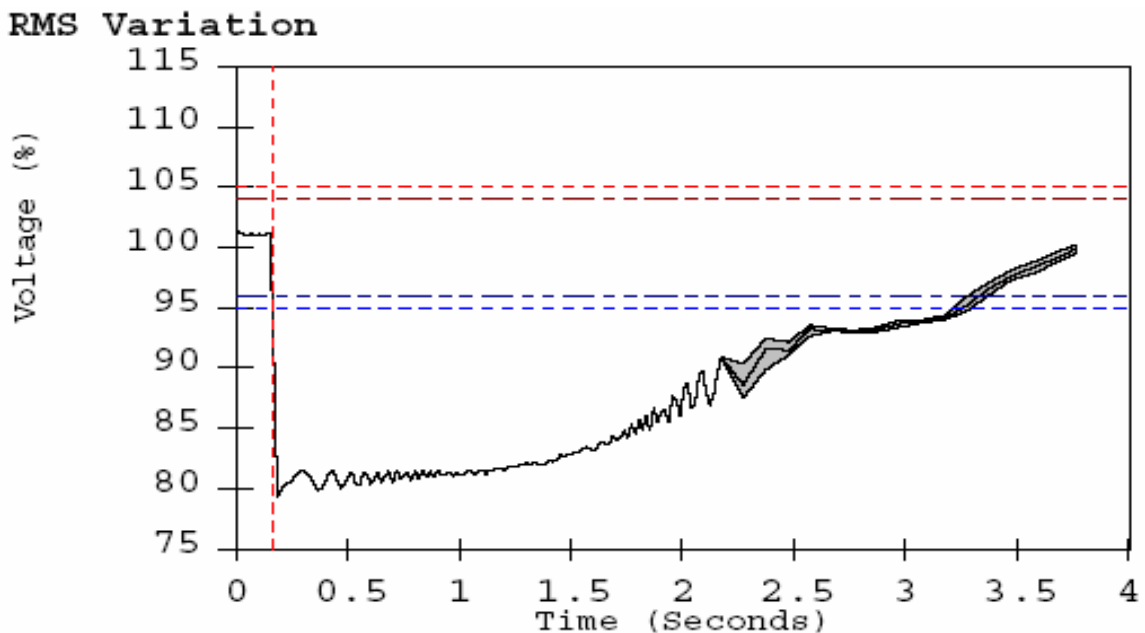


Figure 4-3-Temporary voltage sag caused by motor starting [34]

4.2.4 Swell

An increase in rms voltage or current at the power frequency for durations from 0.5 cycles to 1 min. Typical values are 1.1 - 1.8 p.u [34]. A swell can occur due to a single line-to-ground fault on the system resulting in a temporary voltage rise on the unfaulted phases and also be caused by switching off a large load or switching on a large capacitor bank.

RMS Variation

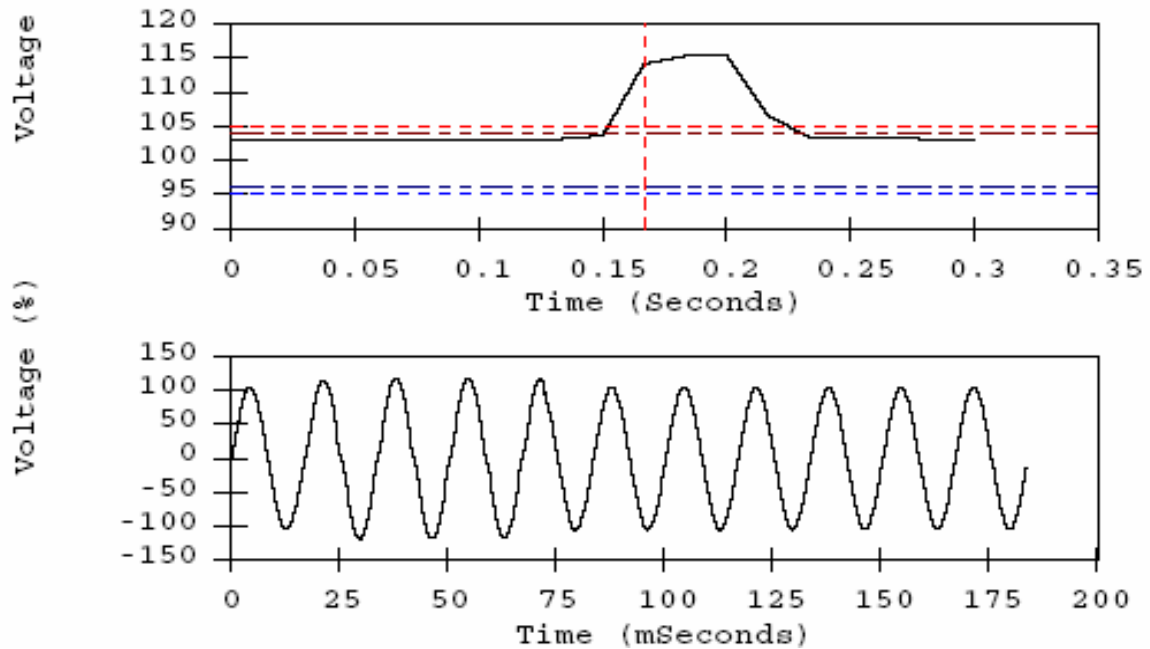


Figure 4-4- illustrates a voltage swell caused by a SLG fault [34]

4.2.5 Transient

A phenomenon or a quantity which varies between two consecutive steady states during a time interval that is short compared to the time scale of interest. A transient can be a unidirectional impulse of either polarity or a damped oscillatory wave with the first peak occurring in either polarity. [35]

Broadly speaking, transients can be classified into two categories, impulsive and oscillatory. These terms reflect the wave shape of a current or voltage transient.

An impulsive transient is a sudden, non-power frequency change in the steady state condition of voltage, current, or both, that is unidirectional in polarity (primarily either positive or negative). The most common cause of impulsive transients is lightning

Oscillatory transient is a sudden, non-power frequency change in the steady state condition of voltage, current, or both, that includes both positive and negative polarity values. It is described by its spectral content (predominant frequency), duration, and magnitude.

4.3 Distributed Generation and Power Quality

A common belief among developers is that DG will improve power quality, and this potential for better quality is mentioned as one of the value attributes of installing distributed generators. In some cases distributed generation and storage are being promoted as an answer to the best quality power requirements of high technology or sensitive end use customers. Whether or not this valuable attribute of DG is valid will depend on the specific technologies, site conditions and potential interaction with the existing electric power system.

4.3.1 Summary of DG Impacts on power quality

DG can improve regulation or cause problems with regulation. The main ways that DG can cause regulation problems are:

- ✓ **Low voltage due to DG just downstream of a regulator with line-drop compensation:**

Line drop compensation is the technique commonly applied by LTC transformer controllers and line voltage regulators to control the voltage on the distribution system based on the line current. Under heavy load, a generator just downstream of the generator will reduce the observed load on the feeder (so the regulator will not boost the voltage as much). This leads to lower voltage downstream of the regulator.

- ✓ **High voltage due to DG:**

High voltages may be caused by reverse power flow. Under light load for a location where the primary voltage is already high, the voltage rise can be enough to push the voltage above nominal limits. This can even happen for a small DG located on the secondary because of the voltage drop along the service drop, the secondary wiring, and the distribution transformer.

- ✓ **Interaction with regulating equipment:**

Another area of concern is with interaction of regulation equipment and DG. If the DG has varying output, it may change the system voltage or current flows enough to cause a regulator tap change or an operation of a switched capacitor. Likewise, a distributed generator that has feedback to control voltage may interact negatively to the utility regulation equipment. There may be undesirable cycling of regulation devices and noticeable power quality impacts under such conditions.

4.3.2 DG-Caused High Voltages

There are also concerns with DG causing high voltages on distribution circuits because of reverse power flow. It is possible to estimate the effect of a generator by using the standard voltage drop equations with reverse power flow. The voltage drop along a feeder due to a load is approximately equal to:

$$V_{drop} = I_R R + I_X X \dots\dots\dots 4.2$$

Where:

V drop= voltage drop along the feeder

R = line resistance, ohms

X = line reactance, ohms

I_R = line current due to real power flow, amps (negative for a generator injecting power)

I_X = line current due to reactive power flow, amps (negative for a capacitor)

The voltage at the generator can be estimated by taking the highest pre-fault voltage and adding the voltage rise due to the generator from the equation above. Note that this approximation is not a substitute for a proper load flow. It does not fully model the response of the load to the change in voltage, and it does not consider regulator response. It is useful for a first attempt at estimating whether the voltage rise due to the generator might be a problem.

The DG which is exporting mainly real power will cause voltage to go up most where X/R ratios are low. The real power portion will cause the largest voltage rise when the

line resistance is high. If the DG is injecting reactive power like a capacitor or there are fixed capacitors nearby, the voltage rise is even larger. Under the right circumstances, this voltage rise is beneficial (voltage support), but if too much rise occurs or it occurs on a section of feeder where the voltage was already near the upper normal limit before the DG started, then a high voltage problem may be created (see Figure 4-9). If voltage rise can be a problem, there are several options. One would be to limit the size of the generator to below the level necessary to cause problems

Another would be to relocate the DG to a more suitable location on the distribution circuit. On the DG side, the generator could be operated to absorb more reactive power (by removing local capacitors or operating a synchronous generator).

This is the opposite of what is normally done and reduces the T&D support value of DG.

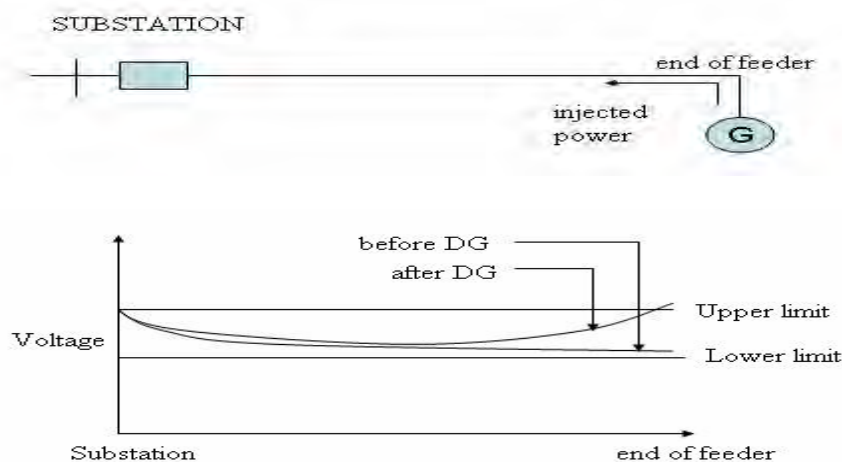


Figure 4-9- Voltage profile on feeder before and after addition of large DG. High voltage may occur at the end due to the voltage rise caused by the DG injected power [36]

Reducing the power factor of the generator causes voltage drop due to the reactive component of the generator. This approach may increase losses on the feeder, however, and result in an effective reduction in available capacity on the feeder.

4.4 The concept of Distribution System Reliability

The function of an electric power system is to satisfy the system load requirement with a reasonable assurance of continuity and quality. The ability of the system to provide an

adequate supply of electrical energy is usually designated by the term reliability. The concept of power-system reliability is extremely broad and covers all aspects of the ability of the system to satisfy the customer requirements. There is a reasonable subdivision of the concern designated as system reliability which is shown in Figure 4.10.

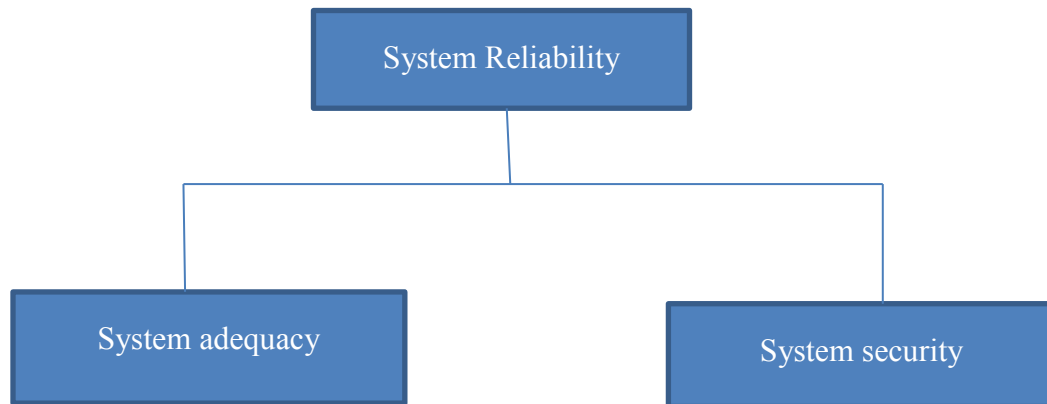


Figure 4-10- System Reliability Subdivisions

Adequacy: Relates to the existence of sufficient facilities within the system to satisfy the consumer load demand. These include

- The facilities necessary to generate sufficient energy and
- The associated transmission and distribution facilities required to transport the energy to the actual consumer load points.

Security: Relates to the ability of the system response to disturbances arising within that system. Security is therefore associated with the response of the system to whatever perturbations it is subject to [37].

4.5 Reliability Indices for Distribution system

To measure system performance, the electric utility industry has developed several performance measures of reliability. These reliability indices include measures of outage duration, frequency of outages, system availability, and response time

4.5.1 The common distribution reliability indices

The most common distribution reliability indices include the System Average Interruption Duration Index (SAIDI), Customer Average Interruption Duration Index (CAIDI), System Average Interruption Frequency Index (SAIFI), Momentary Average Interruption Frequency Index (MAIFI), Customer Average Interruption Frequency Index (CAIFI) Customers Interrupted per Interruption Index (CIII), and the Average Service Availability index (ASAI). Each of these indices will be discussed below one by one

4.5.1.1 System Average Interruption Duration Index (SAIDI)

The most often used performance measurement for a sustained interruption is the System Average Interruption Duration Index (SAIDI). This index measures the total duration of interruption, for the average customer during a given time period. SAIDI is normally calculated on either monthly or yearly basis; however, it can also be calculated daily, or for any other time period. The formula is

$$SAIDI = \frac{\sum (r_i * N_i)}{NT} \dots\dots\dots 4.3$$

Where,

r_i = Restoration time, minutes.

N_i = Total number of customers interrupted

NT = Total number of customers

4.5.1.2 Customer Average Interruption Duration Index (CAIDI)

Once an outage occurs, the average time to restore service is found from Customer Average Interruption Duration Index (CAIDI)

CAIDI is calculated similar to SAIDI except that the denominator is the number of customers interrupted versus the total number of utility customers. CAIDI is,

$$CAIDI = \frac{\sum (r_i * N_i)}{\sum N_i} \dots\dots\dots 4.4$$

Where

r_i = Restoration time, minutes.

N_i = Total number of customers interrupted

4.5.1.3 System Average Interruption Frequency Index (SAIFI)

The System Average Interruption Frequency Index (SAIFI) is the average number of times that a system customer experiences an outage during the year (or time period under study) and it is a dimensionless number.

$$SAIFI = \frac{\sum N_i}{NT} \dots\dots\dots 4.5$$

Where

N_i = Total number of customers interrupted

NT = Total number of customers

SAIFI can also be found by dividing the SAIDI value by the CAIDI value,

$$SAIFI = \frac{SAIDI}{CAIDI} \dots\dots\dots 4.6$$

4.5.1.4 Customer Average Interruption Frequency Index (CAIFI)

Similar to SAIFI is CAIFI, which is the Customer Average Interruption Frequency Index. The CAIFI measures the average number of interruptions per customer interrupted per year. The CAIFI is,

$$CAIFI = \frac{\sum N_o}{\sum N_i} \dots\dots\dots 4.7$$

Where

N_o = Number of interruptions

N_i = Total number of customers interrupted

4.5.1.5 Customer Interrupted per Interruption Index (CIII)

Customer Interrupted per Interruption Index (CIII) gives the average number of customers interrupted during an outage. It is the reciprocal of the CAIFI and is,

$$CIII = \frac{\sum Ni}{\sum No} \dots\dots\dots 4.8$$

Where

No = Number of interruptions

N_i = Total number of customers interrupted

4.5.1.6 Average Service Availability Index (ASAI)

The Average Service Availability Index (ASAI) is the ratio of the total number of customer hours that service was available during a given time period to the total customer hours demanded. This is sometimes called the service reliability index. The ASAI is usually calculated on either a monthly basis (730 hours) or a yearly basis (8,760 hours), but can be calculated for any time period. The ASAI is found as,

$$ASAI = \left[1 - \left(\frac{\sum (ri * Ni)}{NT * T} \right) \right] * 100 \dots\dots\dots 4.9$$

Where,

T = Time period under study, hours.

ri = Restoration time, hours

N_i = Total number of customers interrupted

NT = Total number of customers served

In this calculation, the restoration time, ri, is in hours instead of minutes.

Another way of looking at ASAI on an annual basis is,

$$ASAI = \left[\frac{8760 - SAIDI}{8760} \right] * 100 \dots\dots\dots 6.9$$

4.5.1.7 Total energy not supplied (ENS)

The ENS (Total energy not supplied) is the sum of each load times its outage duration:

$$ENS = L * ri(kwh / yr) \dots\dots\dots 6.10$$

Where

$L = \text{Load (KW)}$

$r_i = \text{Outage Duration}$

4.5.1.8 Average Energy Not Supplied (AENS)

AENS (Average Energy Not Supplied) can be calculated by dividing the ENS and the total number of customers:

$$AENS = \frac{\text{Total Energy not supplied}}{\text{Number of customers}} \text{ (kWh/ customeryr)} \dots\dots\dots 6.11$$

Note: A customer here is defined as an electric meter, which can be an individual customer, a commercial entity or organization etc.

4.6 Distribution System Reliability Improvement by Means of Distributed Generation

Distributed generation and storage have a number of advantages. One of the advantages of DG is the ability to supply loads during a grid failure.

The reliability of the network can be improved if the DG unit is able to supply most of the loads. This requires additional control equipment, additional switchgear and most likely also communication equipment and load shedding protocols. In this thesis I will not address the technical issues involved with islanding, but quantify the improvements that can be obtained when DG is capable of supplying most customers demand.

A number of general conclusions are drawn from the studies, including recommendations for the design of distribution networks such that optimal use is made of the DG units for improving network reliability.

5 Case Study: DG integration to Adama distribution system

5.1 General Information

Software Used

There are currently a wide variety of software applications that can model DG systems, including PSCAD, SKM PowerTools, ETAP and DigSILENT. DigSILENT was chosen as the software application to be used for this simulation.

DigSILENT was chosen because of

- ✓ Economic limitations
- ✓ Its ease of use, as it contains blocks to model most common power system components along with the capability of simulating the components in a steady state and during transient events.

DIgSILENT PowerFactory

DIgSILENT PowerFactory is commercial power system software for use in

- ✓ Analysis of generation, transmission and distribution networks.
- ✓ Power flow calculations and dynamic simulations.

The version used for this thesis is 14.0.524

5.1.1 Adama Distribution System Modeling

The design case study presented here is implemented on the distribution system of Adama town. The single-line diagram of the existing distribution system is shown in Figure 5.1. The objective of this case study is to design an upgraded system that would make Adama's town distribution system a near net-zero consumer interruption. That is to make a facility that has nearly 100% of its energy demand available all the time and generated locally to support the existing grid system. The generation methods used to achieve this goal should use only renewable sources to reduce or eliminate fuel costs, to support research and development in the field of renewable energies, and to foster

environmental responsibility within the area and community. The underlying purpose of this case study is to illustrate how the issues associated with distributed generation will be addressed during design so that the system functionality is optimized and challenging scenarios are avoided.

There are multiple justifications for implementing such a design at Adama town.

- ✓ Firstly, a large town such as Adama has energy demand increasing from time to time. But there is a large interruption of electricity in this town. So, the investments for distributed generation can be justified easily.
- ✓ The town of Adama has high solar insolation levels average $6.06 \text{ kWh/m}^2/\text{d}$ [Nasa] and consistent wind stream averagely **8-10 m/s** [15] areas, which are good for renewable energy application.
- ✓ Furthermore, design and implementation of emerging technologies, such as those of renewable energies, provides resources for application based education in various fields.

With a design focused on renewable energy that addresses all areas of concern discussed in this paper, the Ethiopian electric utility also stands to benefit a great deal from such a project since it would praise their renewable portfolio requirements. With all parties involved in a position to benefit, implementation should be easily accomplished if a design is achieved that ensures safe and reliable service.

The existing system shown in Figure 5.1 was modeled using DIgSilent PowerFactory software. The system loading was derived from metering data gathered from Adama's facilities department. The loading data was used to gain only approximate typical loading, the simulations were performed to account for light and heavy loads that entailed the full range of possible loading. In this high-level model, the various loads on each feeder are modeled as a single lumped load.

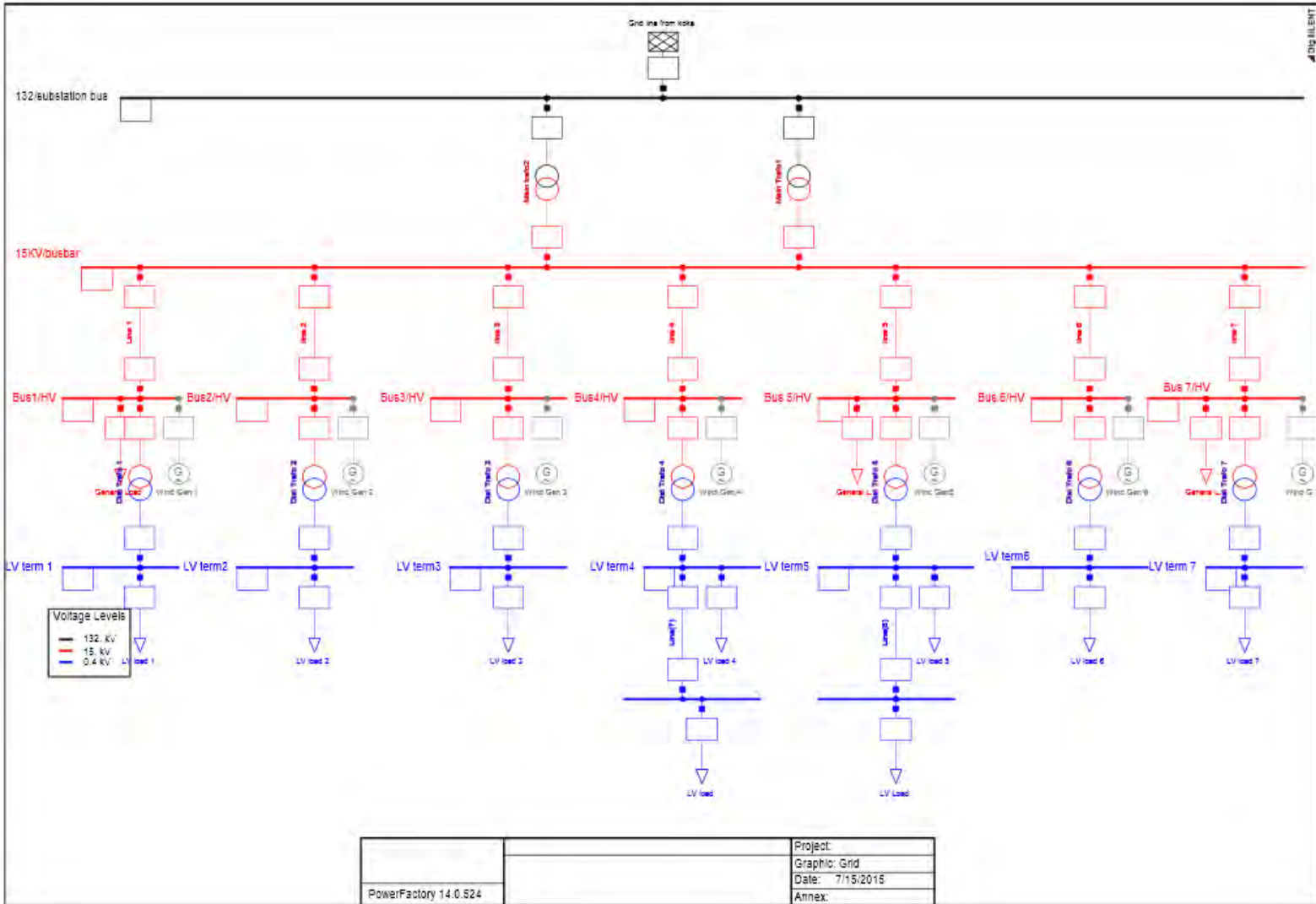


Figure 5-1- Adama Distribution Systems

5.2 Methodology for optimal DG Size and Location

5.2.1 Objective Function

The objective is to maximize capacity of DG integration subject to the constraints outlined in section 3.1.

Generation capacity should be allocated across the buses such that none of the technical constraints are broken and the capacity is maximized. Therefore the proposed objective function is as shown in Equation (5.1).

$$J = \sum_{i=1}^N PDGi \dots \dots \dots 5.1$$

Where PDGi is the DG capacity at the ith bus and N is the number of buses. Without loss of generality, it is assumed that there is one generator connected at each bus. The objective function J (MW), given in Equation (5.1) is maximized subject to the constraints, which are formalized under section 3.1.

5.2.2 Optimal Location of DG based on Voltage Sensitivity Index

In order to restrict solution space to few buses, voltage sensitive buses are first identified by penetrating DG with 25% of the total feeder loading capacity at each bus at a time and then, calculating the voltage sensitivity index (VSI) by using equation 5.2. When DG is connected at bus i, VSI for bus i is defined as [38]:

$$VSI_i = \sqrt{\frac{\sum_{k=1}^n (1 - V_k)^2}{n}} \dots \dots \dots 5.2$$

Where V_k is voltage at k^{th} bus and n is the number of buses.

The bus with least VSI will be picked as the best location for the DG placement.

Therefore by using the above equation the VSI for all the buses are shown in the table shown below.

Table 5-1 Voltage sensitivity index

	BUS 1	BUS 2	BUS 3	BUS 4	BUS 5	BUS 6	BUS 6
VSI	0.5657	0.919234	0.713378	1.201241	0.223146	0.661870	0.807141

From the voltage sensitivity index calculated above the best location for placing DG will be Bus5 and Bus1 respectively as they have the least VSI.

5.2.3 Optimal size of DG

This section elaborates the detailed description of the mathematical steps taken to formulate an expression for finding optimal DG sizes for given specific number of buses. The method explained here is for the case when two DGs are placed simultaneously,

while considering the optimal power factor, which can be generalized for placement of any number of DGs in the system.

5.2.4 Distribution System Power Losses

Based on the active and reactive power injections at the buses, total real power loss in an n bus system is given as [39]:

$$P_L = \sum_{i=1}^n \sum_{j=1}^n [\alpha_{ij}(P_i P_j + Q_i Q_j) + \beta_{ij}(Q_i P_j - Q_j P_i)] \dots \dots \dots 5.3$$

Where

$$\alpha_{ij} = \frac{R_{ij}}{|v_i||v_j|} \cos(\delta_i - \delta_j) \text{ and } \beta_{ij} = \frac{R_{ij}}{|v_i||v_j|} \sin(\delta_i - \delta_j)$$

$P_i P_j$ Active power injections at the i^{th} and j^{th} buses, respectively; Q_i, Q_j Reactive power injections at the i^{th} and j^{th} buses, respectively; $v_i \angle \delta_i$ and $v_j \angle \delta_j$ are Complex voltages at the i^{th} and j^{th} buses, respectively; $R_{ij} + jX_{ij}$ ij^{th} element of impedance matrix [Zbus]; n total number of buses in the system.

5.2.5 Analytical Expressions for the Proposed Method:

This sub-section introduces the extensive mathematical steps taken to finalize the expressions for calculating the size of DGs at two buses simultaneously, while considering the optimal power factor.

For a DG, reactive power injection is given as [39]:

$$Q_{DGi} = aP_{DGi} \dots \dots \dots 5.4$$

Where

$$a = (\text{sign}) \tan(\cos^{-1}(PF_{DG})) \dots \dots \dots 5.5$$

Sign = +1 for DG injecting reactive power or -1 DG consuming reactive power; PF_{DG} is power factor of DG.

Active and reactive power injections at the bus where DG is installed are given, in terms of active and reactive power demands P_{Di} and Q_{Di}

$$P_i = P_{DGi} - P_{Di} \dots \dots \dots 5.6$$

$$Q_i = Q_{DGi} - Q_{Di} = aP_{DGi} - Q_{Di} \dots \dots \dots 5.7$$

By substituting (5.6) and (5.7) in (5.3), the active power loss becomes:

$$P_L = \sum_{i=1}^n \sum_{j=1}^n \left[\alpha_{ij} \{ (P_{DG_i} - P_{D_i}) P_j + (a P_{DG_i} - Q_{D_i}) Q_j \} + \beta_{ij} \{ (a P_{DG_i} - Q_{D_i}) P_j - (P_{DG_i} - P_{D_i}) Q_j \} \right] \dots\dots\dots 5.8$$

It can be proved that the minimum of active power loss of the system can be found if partial derivative of (5.8) with respect to injected real power from DG at i^{th} bus computed equal to zero. Hence, (5.8) can be written as:

$$\frac{\partial P_L}{\partial P_{DG_i}} = 2 \sum_{j=1}^n \left[\alpha_{ij} (P_j + a Q_j) + \beta_{ij} (a P_j - Q_j) \right] = 0 \dots\dots\dots 5.9$$

As mentioned earlier, the method for calculating the optimum size of two DGs is presented here. Supposing the DGs are to be placed at bus number “x” and “y”, (5.9) can be rewritten as:

$$\frac{\partial P_L}{\partial P_{DG_x}} = \alpha_{xx} (P_x + a Q_x) + \beta_{xx} (a P_x - Q_x) + \alpha_{xy} (P_y + a Q_y) + \beta_{xy} (a P_y - Q_y) + \sum_{\substack{j=1 \\ j \neq x,y}}^n (\alpha_{xj} P_j - \beta_{xj} Q_j) + a \sum_{\substack{j=1 \\ j \neq x,y}}^n \alpha_{xj} Q_j + \beta_{xj} P_j = 0 \dots\dots\dots 5.10$$

$$\frac{\partial P_L}{\partial P_{DG_y}} = \alpha_{yy} (P_y + a Q_y) + \beta_{yy} (a P_y - Q_y) + \alpha_{yx} (P_x + a Q_x) + \beta_{yx} (a P_x - Q_x) + \sum_{\substack{j=1 \\ j \neq y,x}}^n (\alpha_{yj} P_j - \beta_{yj} Q_j) + a \sum_{\substack{j=1 \\ j \neq y,x}}^n \alpha_{yj} Q_j + \beta_{yj} P_j = 0 \dots\dots\dots 5.11$$

The terms taken out of the summation are actually the coupling effect factors of both DGs on each other. This fact must be considered, for calculating the best DG sizes otherwise it leads to considerable errors in the results.

While calculating sizes of two or more DGs simultaneously, and considering the interdependencies and coupling effects, the best possible size for reducing the losses can be determined.

$$\begin{aligned}
 & \left. \begin{aligned}
 X_x &= \sum_{\substack{j=1 \\ j \neq x,y}}^n (\alpha_{xj} P_j - \beta_{xj} Q_j) + a \sum_{\substack{j=1 \\ j \neq x,y}}^n \alpha_{xj} Q_j + \beta_{xj} P_j \\
 &= \sum_{\substack{j=1 \\ j \neq x,y}}^n (\alpha_{xj} P_j - \beta_{xj} Q_j) + a(\alpha_{xj} Q_j + \beta_{xj} P_j). \\
 \text{let } X_y &= \sum_{\substack{j=1 \\ j \neq y,x}}^n (\alpha_{yj} P_j - \beta_{yj} Q_j) + a \sum_{\substack{j=1 \\ j \neq y,x}}^n \alpha_{yj} Q_j + \beta_{yj} P_j \\
 &= \sum_{\substack{j=1 \\ j \neq y,x}}^n (\alpha_{yj} P_j - \beta_{yj} Q_j) + a(\alpha_{yj} Q_j + \beta_{yj} P_j) \dots\dots\dots 5.12
 \end{aligned} \right\}
 \end{aligned}$$

Also, $\beta_{ii} = 0$ $\alpha_{ij} = \alpha_{ji}$ and $\beta_{ij} = -\beta_{ji}$ hence, (5.10) and (5.11) become:

$$\alpha_{xx} P_x + \alpha_{xx} a Q_x + P_y (\alpha_{xy} + \beta_{xy} a) + Q_y (\alpha_{xy} a - \beta_{xy}) + X_x = 0 \dots\dots\dots 5.13$$

$$\alpha_{yy} P_y + \alpha_{yy} a Q_y + P_x (\alpha_{yx} + \beta_{yx} a) + Q_x (\alpha_{yx} a - \beta_{yx}) + X_y = 0 \dots\dots\dots 5.14$$

By substituting (5.6) and (5.7) in (5.13) and (5.14) and arranging for DG sizes,

$$\begin{aligned}
 P_{DGx} &= \\
 & \frac{P_{Dx} (\alpha_{xx} \alpha_{yy} - \alpha_{yx}^2 - \alpha_{xy} \beta_{yx} a) + Q_{Dx} (\alpha_{xx} \alpha_{yy} a - a^2 a + \alpha_{xy} \beta_{yx}) + \alpha_{yy} \beta_{xy} (P_{Dy} a - Q_{Dy}) - \alpha_{yy} X_x + \alpha_{xy} X_y}{(\alpha_{xx} \alpha_{yy} - \alpha_{xy}^2)(1 + a^2)} \dots\dots\dots 5.15
 \end{aligned}$$

$$\begin{aligned}
 P_{Dgy} &= \\
 & \frac{P_{Dy} (\alpha_{xx} \alpha_{yy} - \alpha_{yx}^2 - \alpha_{xy} \beta_{yx} a) + Q_{Dy} (\alpha_{xx} \alpha_{yy} a - a^2 a + \alpha_{xy} \beta_{yx}) + \alpha_{xx} \beta_{yx} (P_{Dx} a - Q_{Dx}) - \alpha_{xx} X_y + \alpha_{yx} X_x}{(\alpha_{xx} \alpha_{yy} - \alpha_{xy}^2)(1 + a^2)} \dots\dots\dots 5.16
 \end{aligned}$$

$$\text{let } \begin{cases} A_{xy} = \alpha_{xx} \alpha_{yy} - \alpha_{xy}^2 \\ aA_{xy} = a(\alpha_{xx} \alpha_{yy} - \alpha_{xy}^2) \end{cases} \text{ and } \begin{cases} C_y = P_{Dy} a - Q_{Dy} \\ Cx = P_{Dx} a - Q_{Dx} \end{cases}$$

So the general form can now be written as

$$P_{DGx} = \frac{P_{Dx}(A_{xy} - \alpha_{xy} \beta_{yx} a) + Q_{Dx}(aA_{xy} + \alpha_{xy} \beta_{yx}) + \alpha_{yy} \beta_{yx} (C_y) - \alpha_{yy} X_x + \alpha_{xy} X_y}{A_{xy}(1 + a^2)} \dots\dots\dots 5.17$$

$$P_{DGy} = \frac{P_{Dy}(A_{xy} - \alpha_{xy} \beta_{yx} a) + Q_{Dy}(aA_{xy} + \alpha_{yx} \beta_{yx}) + \alpha_{xx} \beta_{yx} (C_x) - \alpha_{xx} X_y + \alpha_{yx} X_x}{A_{xy}(1 + a^2)} \dots\dots\dots 5.18$$

Each of these equations gives the optimum size of DGs at the respective buses while inhibiting the impact of DG at the other bus location. These are generalized equations for placing two DGs simultaneously. Suppose, two DGs need to be placed at buses “1” and “5”, the solution would be:

$$P_{DG1} = \frac{P_{D1}(A_{15} - \alpha_{15} \beta_{51} a) + Q_{D1}(aA_{15} + \alpha_{15} \beta_{51}) + \alpha_{55} \beta_{15} (C_5) - \alpha_{55} X_1 + \alpha_{15} X_5}{A_{15}(1 + a^2)} \dots\dots\dots 5.19$$

$$P_{DG5} = \frac{P_{D5}(A_{15} - \alpha_{51} \beta_{15} a) + Q_{D5}(aA_{15} + \alpha_{51} \beta_{15}) + \alpha_{11} \beta_{51} (C_1) - \alpha_{11} X_5 + \alpha_{51} X_1}{A_{15}(1 + a^2)} \dots\dots\dots 5.20$$

Using similar mathematical steps, the analytic expressions for optimal sizes for any number of DGs can be found.

5.2.6 Optimal Power Factor:

To make these expressions useable for practical cases, the power factor demanded from a DG is also incorporated in these expressions. A large distribution system can be summed up as a simple two bus distribution system containing a DG, as shown in Fig. 5.2:

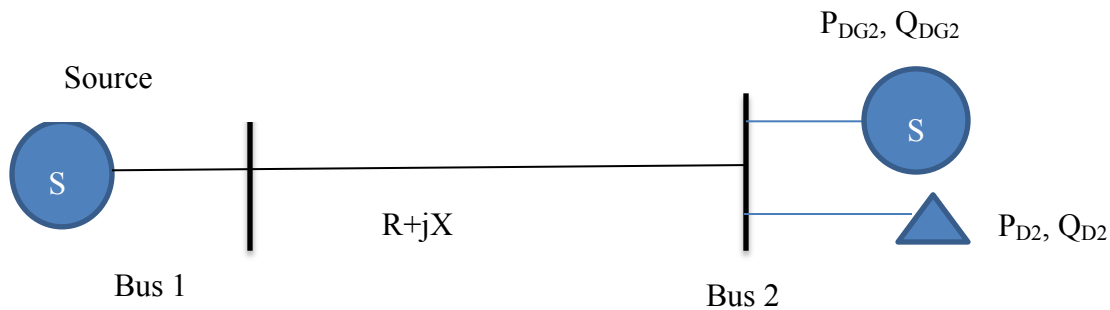


Figure 5-2 Simplified two bus systems

Where load power factor can be given as:

$$PF_{D2} = \frac{P_{D2}}{\sqrt{P_{D2}^2 + Q_{D2}^2}} \dots\dots\dots 5.21$$

This can be proved equal to power factor of DG, and given by:

$$PF_{D2} = PF_{DG2} = \frac{P_{DG2}}{\sqrt{P_{DG2}^2 + Q_{DG2}^2}} = \frac{P_{D2}}{\sqrt{P_{D2}^2 + Q_{D2}^2}} \dots\dots\dots 5.22$$

Where, P_{D2} and Q_{D2} are the summed up active and reactive power demands of whole system. It is assumed that possible minimum in total losses occur at $PF_{D2} = PF_{DG2}$

Using (5.4) and (5.22), “a” can be calculated and hence the DG sizes can be computed.

Algorithm for Optimum Size Calculation

Figure 3 illustrates the flow chart of the computational steps needed to find the results based on proposed analytical expressions. For the sake of illustration, case of placing two DGs is considered here.

1. Enter the number of DGs and number of buses for which optimum size needs to be calculated.
2. Run base case load flow
3. Calculate Power factor of DG using (5.20).
4. Based on input data in step 1 find optimal size of DGs using expression given in (5.15) and (5.16).
5. Place DGs with the given size in the system and calculate the losses.

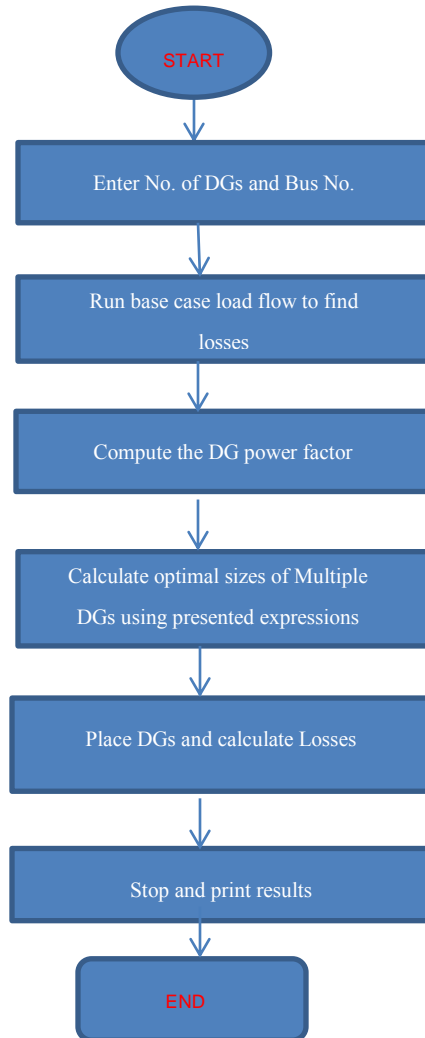


Figure 5-3- Flow chart for optimum size calculations steps

5.3 Test System & Characteristics of Constraint

The methodology was tested on Adama distribution network. The network is modeled by using DigSilent power factory as shown in figure 5.4.

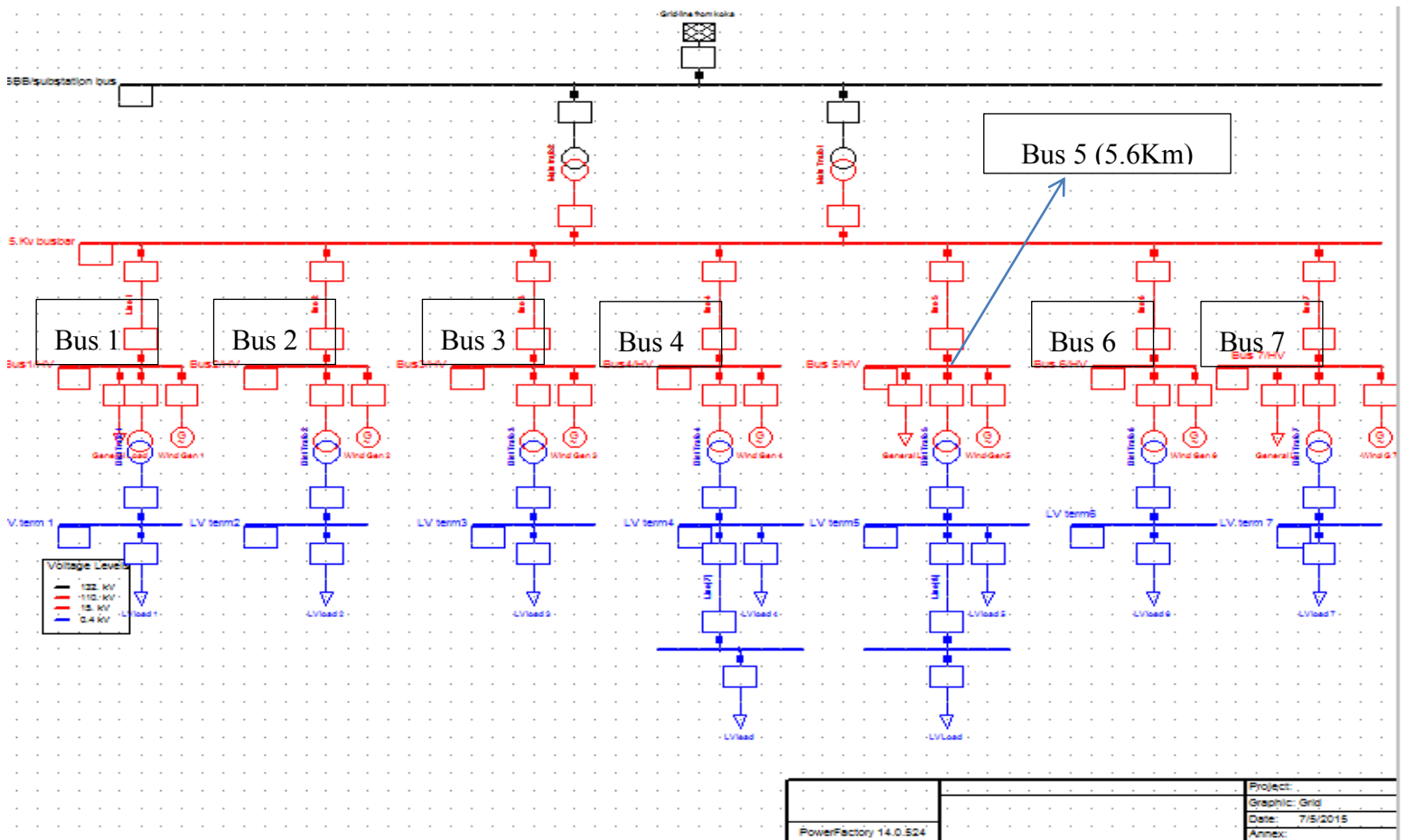


Figure 5-4- 15kV 7 bus and 0.4kV 9 bus radial distribution network diagram

Results are given here for a 132/15 kV station with 7 buses and demonstrates the potential for DG integration.

The individual voltage sensitivity characteristics were calculated and are shown in table 5.2. Bus 5 is the least sensitive to power injections which also matches with the voltage sensitivity index calculated by using the equation of voltage sensitivity. Bus 5 is the least sensitive to power injections due to its proximity to the 132kV station.

Therefore based on this constraint bus 5 will have the largest allocation of generation compared to the other buses. It can also be seen that bus 2 and bus 4 have very similar profiles because, they are found at nearly the same distance to 132kV station and far relative to others which explains significantly lower voltage at these buses.

The values for μ_i (kV/MW) in Equation (3.10) are determined by installing DGs with different power rating at each bus until the constraint limit was exceeded. They are

shown in Table 5.2 as the diagonal elements. The values for β_i (kV) are also shown in this table. The values for μ_{ji} (kV/MW) are also determined and are shown as the off diagonal elements in Table 5.2.

Table 5-2-Voltage Interdependency (kV/MW)

μ in kV/M	BUS 1	BUS 2	BUS 3	BUS 4	BUS 5	BUS 6	BUS 7	β (KV)
BUS 1	1.163954	0.00532	0.003305	0.009539	0.003701	0.004258	0.003393	7.53471
BUS 2	0.020646	1.371155	0.001036	0.00294	0.001161	0.001336	0.001064	10.76229
BUS 3	0.018738	0.001425	0.781745	0.002509	0.00099	0.001139	0.000907	14.63967
BUS 4	0.027765	0.002713	0.001682	1.414529	0.001885	0.002169	0.001727	9.125255
BUS 5	0.039066	0.004747	0.002948	0.008262	0.29687	0.003799	0.003026	13.27144
BUS 6	0.025469	0.002354	0.001459	0.004129	0.001635	0.965636	0.001498	12.07759
BUS 7	0.028435	0.002815	0.001746	0.004931	0.001956	0.002251	0.483572	14.28859

The graph for individual bus voltage sensitivities to power injections at buses is shown in Figure 5.5

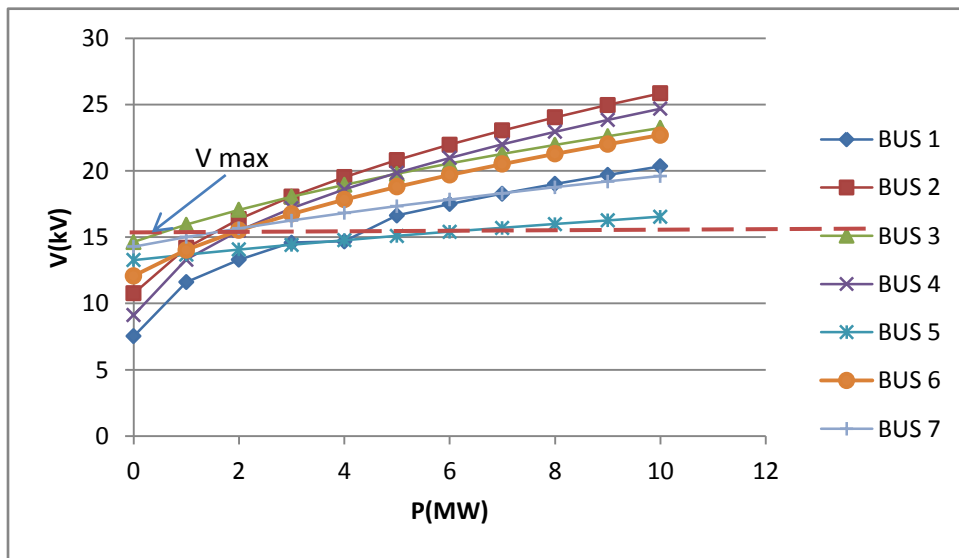


Figure 5-5-Individual bus voltage sensitivities to power injections at buses

The interdependence of voltage was also calculated and the dependence of bus voltage on power injection at bus 5 is shown below.

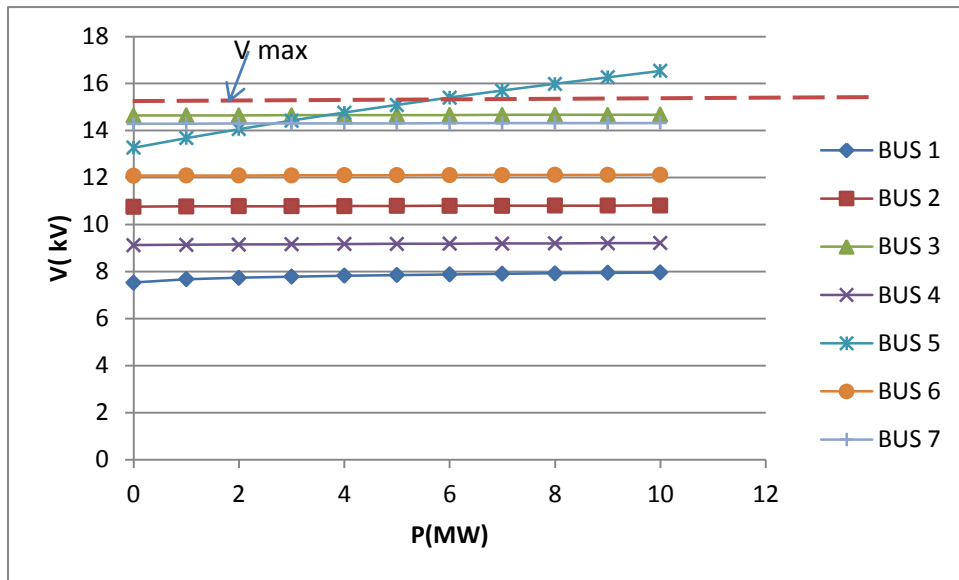


Figure 5-6- Dependence of bus voltages on power injections at bus 5

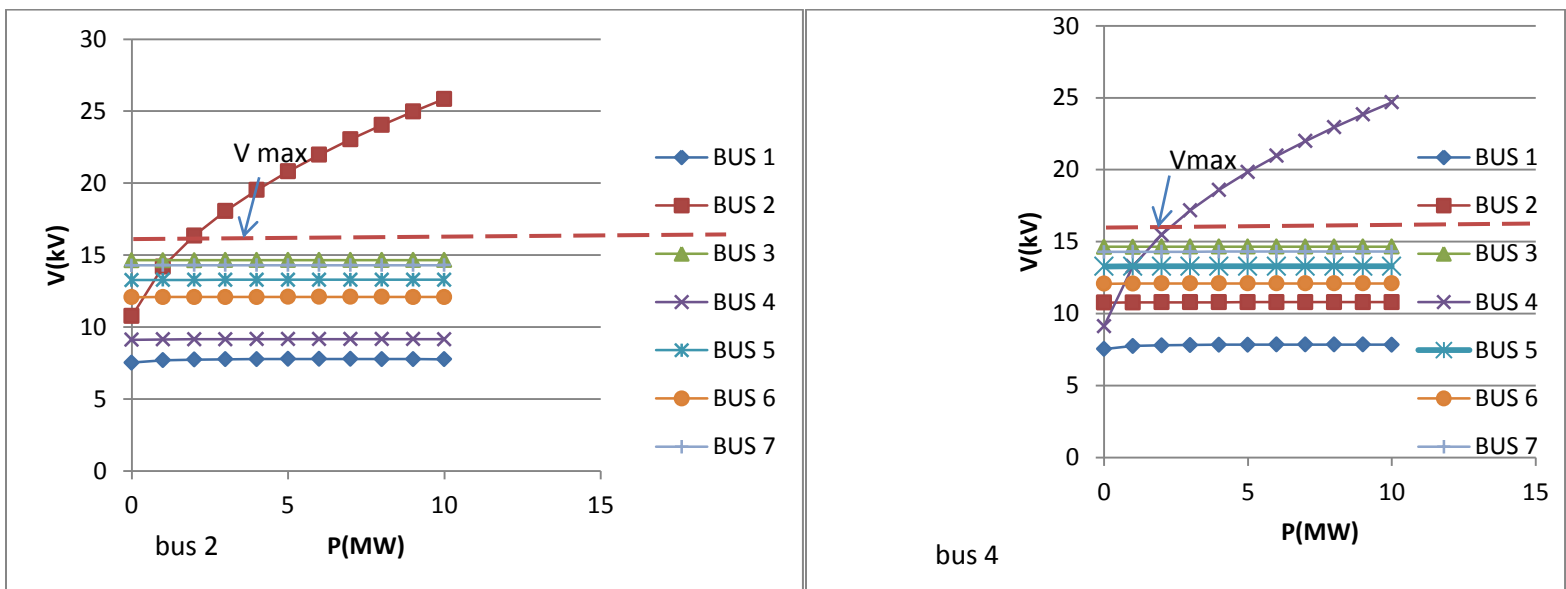


Figure 5-7- Dependence of bus voltages on power injections at bus 2 and 4.

From Figure 5-7 we can see that bus 2 and bus 4 have similar characteristics to the power injection at their buses. This is because they both found nearly at the same distance from 132 KV substation and they are very far relative to the other buses in the network. Comparing the graph shown on figure 5.6 and 5.7 we can observe that for bus 5 the

voltage exceeds the maximum value after we installed 8MW while for bus 2 and 4 the voltage exceeds the maximum value after we install only 2MW. As explained above this result is because of their location from the 132 KV station. Bus 5 is located at **5.6km** while bus 2 is located **39.23** and bus 4 is located at **34.75** from the 132KV station. Therefore bus 5 is less sensitive to power injection

The individual sensitivity of the SCL at the 132/15kV station to power injections at individual buses is also calculated, resulting in Figure 5.8. As would be expected the effect of the buses on the SCL at the 132kV station is dependent on the distance from the station. Relative to the other buses, bus 5 is very close to the 132kV station and as such has a much bigger impact on the SCL at that station.

The values for δjTx (kA/MW) used in (3.4) are shown in Table 5.3

Table 5-3- SCLTx Dependency (kA/MW)

	BUS 1	BUS 2	BUS 3	BUS 4	BUS 5	BUS 6	BUS 7
δTx	0.539	0.25	0.455	0.298	1.731	0.454	0.932

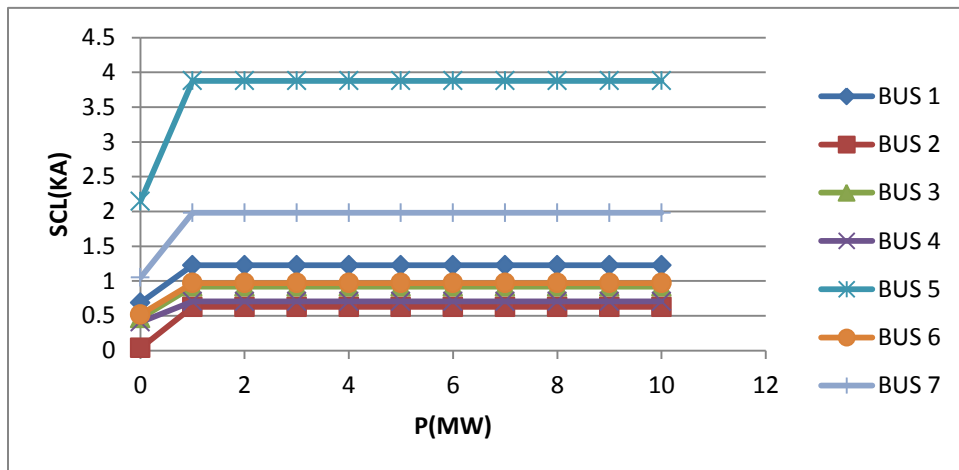


Figure 5-8-Individual dependency of SCL on power injection at different buses

5.4 Optimal allocation Result

The power loss before DG integration is **3.87 MW**. Therefore by applying equation 5.19 and 5.20 the maximum DG that should be installed at bus 5 and bus 1 are determined and the power loss before DG integration and after DG integration were compared as shown in table 5.4.

Table 5-4 location of DG for optimal placement

Case I	No Generation at the buses	Power loss (MW)
	$PD_i=0$	3.87
Case II	Generation at buses (Mw)	Power loss
	$PD_1=4$	0.44
	$PD_5=8$	
	Total=12	

From the above table we can see that with the best location and DG capacity, the power loss has been highly decreased. For this distribution system a total power of **12 MW** can be installed without passing the limits which are kept for the constraints. The power loss was also decreased from **3.87** to **0.44** which is about **88.63%** improvement compared to the power loss without DG integration.

The power generation at case II is obtained by applying equation 5.2, 5.19 and 5.20.

5.4.1 Reliability Analysis by Employing DG

The main purpose of this section is to study the reliability improvement due to the employment of distributed generations (DG) to distribution system. The system under this study is from Adama distribution system. Data of geographic information systems (GIS) including the distance of distribution line and location of load that are parameter of ADS is simulated using digital simulation and electrical network calculation program (DIgSILENT) to analyze the impact of installing DG on the reliability of distribution system. The system average interruption frequency index (SAIFI), the system average interruption duration index (SAIDI), customer average interruption frequency index

(CAIFI), customer average interruption duration index (CAIDI), energy not supplied (ENS), average service availability index (ASAI) and average service unavailability index (ASUI) are assessed as index of reliability by comparing the SAIFI, SAIDI, CAIFI, ENS, ASAI, and ASUI between the base case (no DG) and the case when DG is connected to the distribution system. The results can be summarized by focusing on location of DG, the capacity of DG, the size of load, and the distance of load which are factors able to affect the above indexes.

5.5 System Description

The distribution system consists of 159.55 km of the main distribution feeder. The circuit comprises of 458 transformers with total capacity of 135.67 MVA. The peak load used for our study is 11.89MW. The system serves mostly residential and a few industrial units (i.e. most of the loads in Adama town are residential and only few are industrial). The customers can either be on the main distribution line or the 1-phase lateral.

The circuit is fed by 15kV substation termed as „Adama Substation“. Each distributor lateral is considered as one load point. Each load connected to the main distribution line is also considered as one load point.

Power System Simulation using DIgSILENT

To study the reliability, simulations were performed with various changes as follows:

- ✓ Reliability of distribution system with DG and without DG.
- ✓ The location of distributed generators are designated on any bus of distribution system and installed between buses of distribution system.

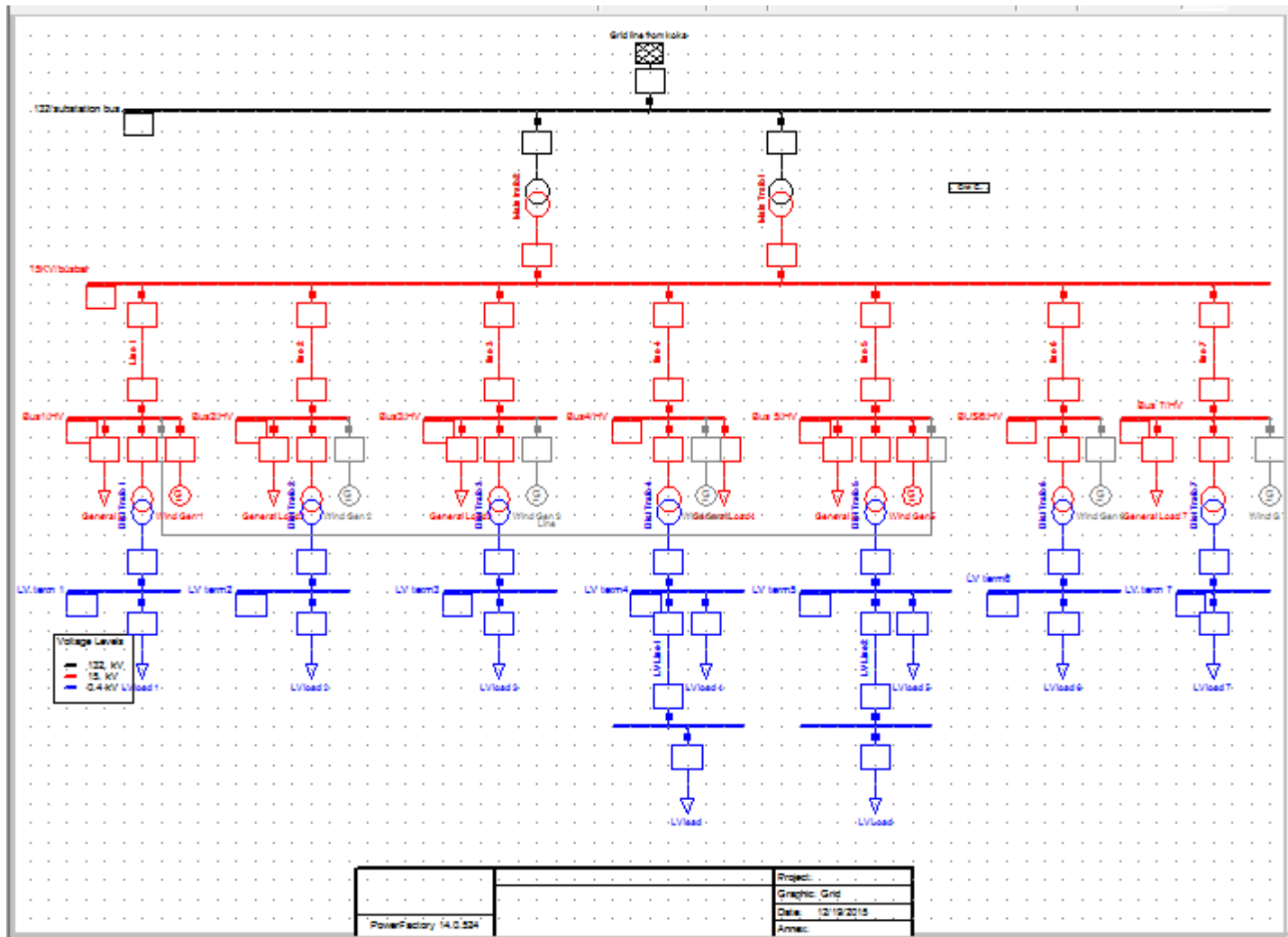


Figure 5-9- A simple radial system with DG connected.

The impact of DG is studied by using different reliability indices in order to evaluate the reliability of the distribution system. The SAIFI, SAIDI, CAIDI, CAIFI, ENS, ASAI, and ASUI, of the base case (without DG) and with DG is compared. The results are shown in table 5.5 and 5.6 respectively below.

The first index, the SAIFI of base case (no DG) is **57.214663** times/customer/year while, Ethiopian electric utility is targeting the SAIFI regulation to change lower than 20-25 times/customer/year. For the best size and location the SAIFI decreases to **21.496565**. The results show that, when location of DG is considered by installing at different buses the reliability of the distribution system decreases but depends on the location of the bus it was installed. For the best size and location it can be seen that the SAIFI decreases with

62.428%. This indicates the utilities will be benefited by employing DG. In addition, when capacity of DG is considered SAIFI varies depending on the size of DG installed. The greater the DG size installed the lower distribution system reliability indices

It is noticed that, when the capacity of DG is increased, SAIFI tends to decrease so reliability of distribution system will be improved.

This also indicates that capacity of DG and location of DG play an important role for reliability improvement in such a system. The different reliability indices of Adama distribution system for the base case and after DG integration are given in the table below.

Table 5-5-The reliability indices for the base case (without DG) integration into distribution system.

Case I	NO Generation at buses(Mw)	Reliability indices
Base case (without DG)	PDG_i=0	SAIFI=57.214663 CAIFI=57.214663 SAIDI=479.667 CAIDI=8.384 ASAI=0.9452423862 ASUI=0.05447576138

Case I

Under this case the Adama distribution system is used without any change to the existing system and by using data obtained from Adama distribution system for reliability analysis.

Table 5-6- The reliability indices in case of 12MW DG installed at distribution system

Case II	Generation at buses(Mw)	Reliability index
After DG Integration	PDG₁=4	SAIFI=21.496565
	PDG₅=8	CAIFI=21.496565 SAIDI=213.721 CAIDI=9.942
	Total =12	ASAI=0.9756025912 ASUI=0.0243974088 ENS=2001.061 AENS=0.310

Case II

Here the reliability of Adama distribution system is analyzed by installing 12 MW DG and keeping the same data used for reliability analysis as of the base case to observe how installing DG will improve the reliability of distribution system.

The following observations can be summarized from reliability analysis:

- Reliability indices (SAIDI, CAIDI and ENS) will not be improved if the DG unit is installed at the distribution substation regardless of the DG size. This is because the failures in any section or distributor lateral within the circuit will not be mitigated as the DG unit will just act as an additional source to the distribution substation. However, in case of power interruptions from the main substation, the DG can be used to supply power to the system.
- Reliability indices (SAIDI, CAIDI and ENS) improve as the DG is installed away from the substation and closer to the loads.
- The best improvement is observed when the DG is placed at the end of the line.

6 Conclusion, Recommendation and Future Work

6.1 Conclusion and Recommendation

This thesis has explained the placement and optimum size of DGs to meet the increment in energy demand and for reducing the active power loss, for a large scale distribution system. The generalized steps toward deriving the analytic expressions for simultaneous optimum sizing, which also include the impact of size of one DG on the others, are presented.

The optimum power factor required from a DG is also incorporated, resulting in the versatility of the derived expressions to be used for DGs with both active and reactive power generation capabilities. The proposed methodology is the general set of steps which can be applied for any number of DGs, but the case with only two DGs is presented here. The least losses can only be possible with optimum sized DG, otherwise the losses may go beyond the value of losses without DG(s), hence the desired benefits from DG placement cannot be achieved.

The methodology was implemented and tested on the Adama distribution network. Results were presented by determining the optimal place and size of DG for this distribution system. Here bus 5 and bus 1 are selected as best place to integrate DG based on voltage sensitivity index and 12MW found to be the maximum size based on power loss reduction and reduces the power loss by **88.63%**.

This thesis also presented the analysis of reliability with the inclusion of DG. The different distribution system reliability indices such as SAIFI, SAIDI, CAIDI CAIFI, before DG integration (base case) and the case when DG is connected to the distribution system were compared. It is shown that by installing DG with proper size and location Adama town distribution system reliability was increased by **62.428%**. It is also shown that distribution system reliability indices depend on both the size and location of DG in the distribution system. Therefore both the location of DG and the capacity of DG must take into account to reach optimal condition in order to create the suitability and fairness for both utility and DG.

In Ethiopia we are mostly using hydroelectric power plant to meet our energy demand and we know that there is high electric interruption which is reported due to decrease in the level of water used for this power generation. Therefore I recommend Ethiopian electric utility to apply the concept of DG integration into distribution system which mostly uses small scale renewable energy technologies and solve the problem associated with the increase in energy demand in our country and increase the reliability of our distribution system

6.2 Future Work

The system costs of integrating distributed generation are not assessed in this thesis which could be a significant constraint. Following this thesis the detailed cost analysis benefits of integrating DG into the distribution network have to be studied and investigated. Further research could also focus on the impacts of DG on islanding.

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Appendix A: System input

Supplying Sub Station	Feeder Line	Line Length In K.M.s	Conductor Type & Size	Voltage Level	Number Of Trafo.s	Total KVA Of The Line
Nazareth S .S.	Line 1 (L1)	19.65	AAC 50 mm ²	15 KV	55	16590
>>	Line 2 (L2)	39.23	AAC 50 mm ²	15 KV	82	29160
>>	Line 3 (L3)	23.52	AAC 50 mm ²	15 KV	88	25860
>>	Line 4 (L4)	34.75	AAC 50 mm ²	15 KV	77	16590
>>	Line 5 (L5)	5.6	AAC 95 mm ²	15 KV	5	9000
>>	Line 6 (L6)	25	AAC 50 mm ²	15 KV	3	8550
>>	Line 7 (L7)	11.8	AAC 50 mm ²	15 KV	11	6765

TABLE B-2: LINE DATA

Line data	R''	Ro''	X''	Xo''	B''	Bo''
	0.6961	1.0875	0.5179	1.4741	3.8259	1.8702

Transformer rating

Transformer type	Transformer Rating	No of Transformer
Main Transformer 1	25MVA	1
Main Transformer 2	25MVA	1
Distribution Transformer 1	0.4MVA	55
Distribution Transformer 2	0.4MVA	82
Distribution Transformer 3	0.3MVA	88
Distribution Transformer 4	0.2MVA	77
Distribution Transformer 5	1.8MVA	5
Distribution Transformer 6	3MVA	3
Distribution Transformer 7	0.8MVA	11

Appendix B: animated load flow before the integration of DG

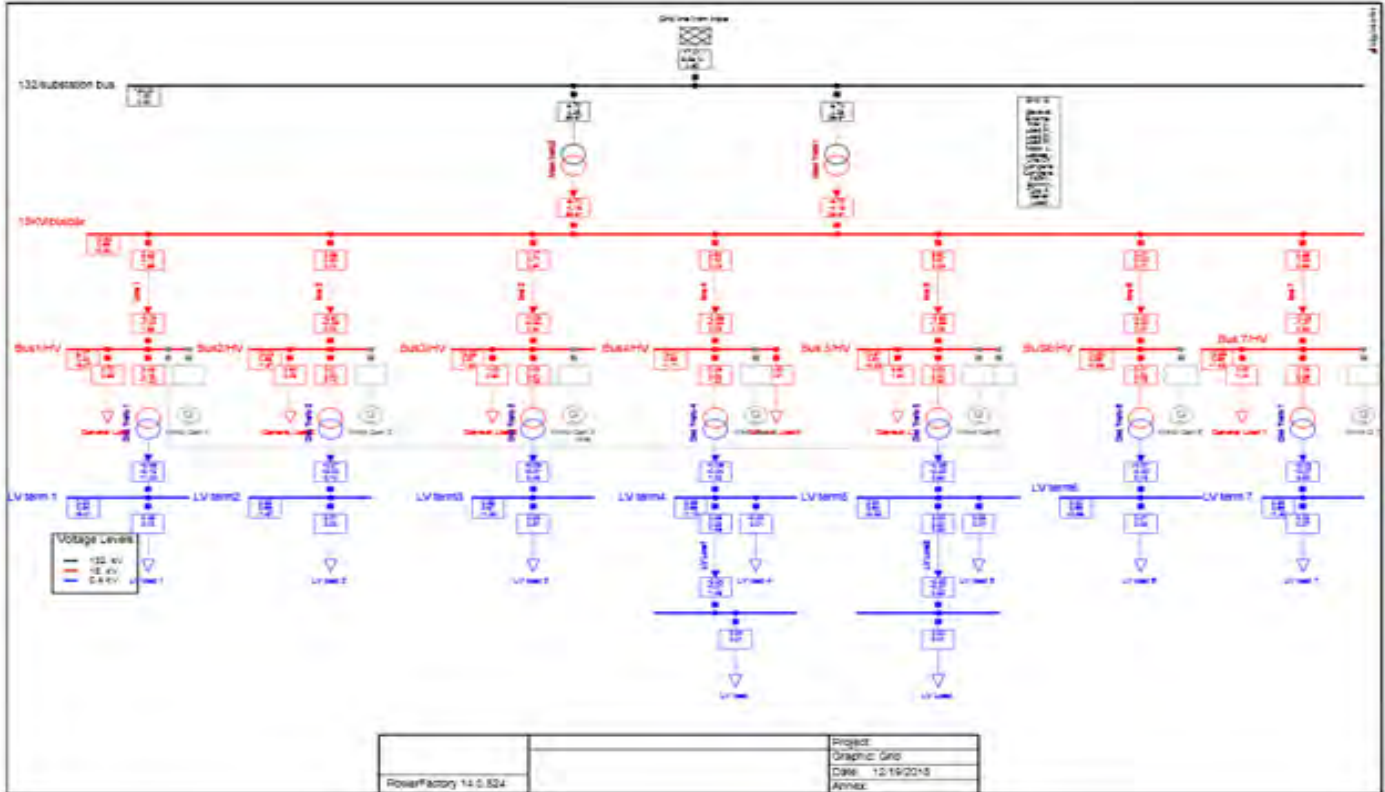


Figure B-1: Animated load flow before integration of DG

Grid: Grid	System Stage: Grid		Study Case: Study Case		Annex: / 1	
Grid: Grid Summary						
No. of Substations	9	No. of Busbars	18	No. of Terminals	132	No. of Lines
No. of 2-w Trfs.	9	No. of 3-w Trfs.	0	No. of syn. Machines	0	No. of asyn. Machines
No. of Loads	15	No. of Shunts	0	No. of SVS	0	
Generation	=	0.00 MW	0.00 Mvar	0.00 MVA		
External Infeed	=	17.41 MW	8.58 Mvar	19.41 MVA		
Inter Grid Flow	=	0.00 MW	0.00 Mvar			
Load P(U)	=	13.53 MW	5.56 Mvar	14.63 MVA		
Load P(Un)	=	13.53 MW	5.56 Mvar	14.63 MVA		
Load P(Un-U)	=	0.00 MW	0.00 Mvar			
Motor Load	=	0.00 MW	0.00 Mvar	0.00 MVA		
Grid Losses	=	3.87 MW	3.02 Mvar			
Line Charging	=		-0.09 Mvar			
Compensation ind.	=		0.00 Mvar			
Compensation cap.	=		0.00 Mvar			
Installed Capacity	=	0.00 MW				
Spinning Reserve	=	0.00 MW				
Total Power Factor:						
Generation	=	0.00	[-]			
Load/Motor	=	0.92 / 0.00	[-]			

Figure B-2: Load flow simulation result before integration of DG

Appendix C: animated load flow after the integration of DG

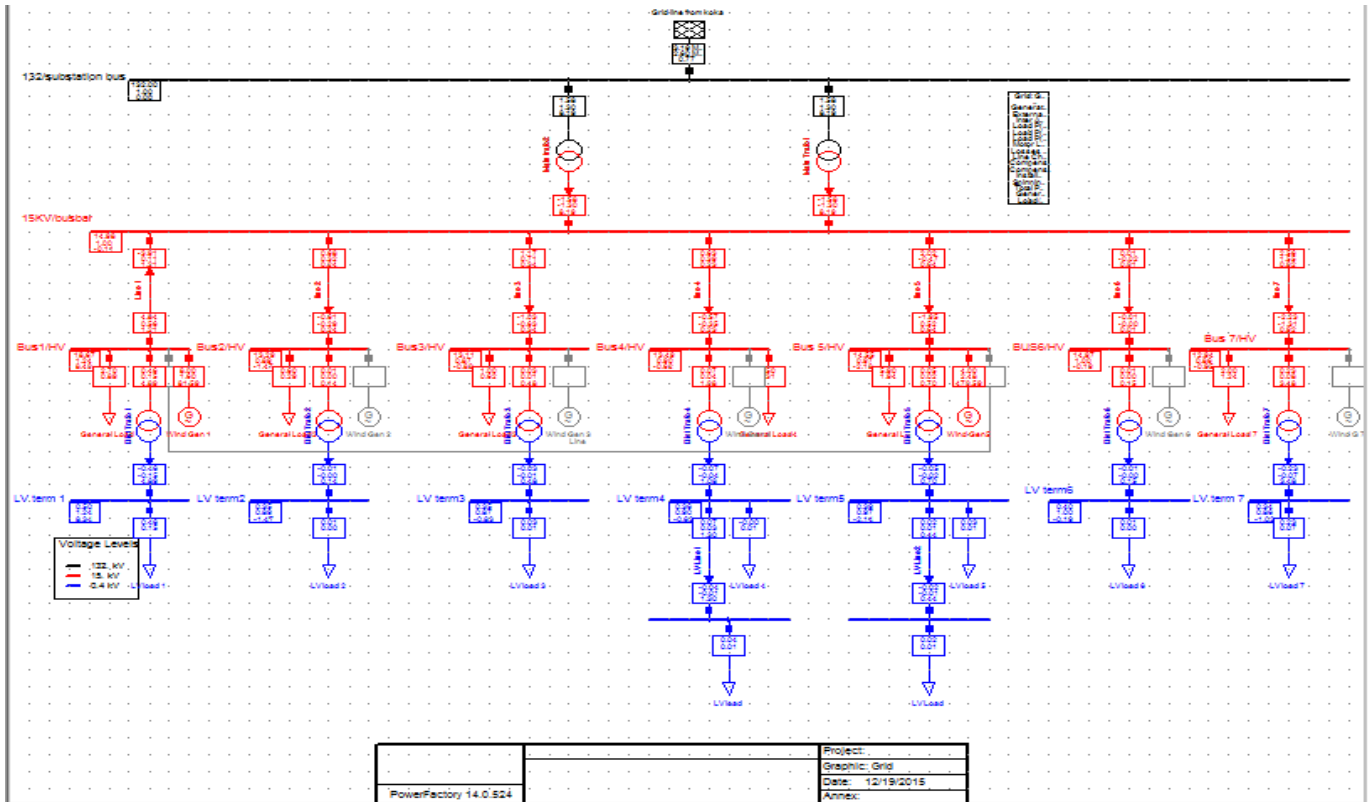


Figure C-1: Animated load flow after integration of DG

Grid: Grid	System Stage: Grid	Study Case: Study Case	Annex: / 1
Grid: Grid Summary			
No. of Substations	9	No. of Busbars	18
No. of 2-w Trfs.	9	No. of 3-w Trfs.	0
No. of Loads	15	No. of Shunts	0
		No. of Terminals	132
		No. of syn. Machines	2
		No. of asyn. Machines	0
		No. of SVS	0
Generation	= 12.00 MW	4.08 Mvar	12.67 MVA
External Infeed	= 3.16 MW	2.60 Mvar	4.10 MVA
Inter Grid Flow	= 0.00 MW	0.00 Mvar	
Load P(U)	= 13.53 MW	5.56 Mvar	14.63 MVA
Load P(Un)	= 13.53 MW	5.56 Mvar	14.63 MVA
Load P(Un-U)	= 0.00 MW	0.00 Mvar	
Motor Load	= 0.00 MW	0.00 Mvar	0.00 MVA
Grid Losses	= 1.63 MW	1.12 Mvar	
Line Charging	=	-0.10 Mvar	
Compensation ind.	=	0.00 Mvar	
Compensation cap.	=	0.00 Mvar	
Installed Capacity	= 8.85 MW		
Spinning Reserve	= -3.15 MW		
Total Power Factor:			
Generation	= 0.95 [-]		
Load/Motor	= 0.92 / 0.00 [-]		

Figure C-2: Load flow simulation result after DG integration

Appendix D: Simulation result for Reliability assessment

		DIGSILENT	Project:				
		PowerFactory	-----				
		14.0.524	Date: 3/4/2015				
Reliability Assessment							
-							
- Network, connectivity analysis							
Selection = Whole System							
Yes = Common mode	Yes = Independent second failures						
Yes = Busbars / terminals	Yes = Double earth faults						
Yes = Lines / cables	No = Maintenance						
Yes = Transformers							
Study Case: Study Case		Annex:	/ 1				
System Summary							
System Average Interruption Frequency Index	:	SAIFI: =	57.214663 1/Ca				
Customer Average Interruption Frequency Index	:	CAIFI: =	57.214663 1/Ca				
System Average Interruption Duration Index	:	SAIDI: =	479.677 h/Ca				
Customer Average Interruption Duration Index	:	CAIDI: =	8.384 h				
Average Service Availability Index	:	ASAI: =	0.9452423862				
Average Service Unavailability Index	:	ASUI: =	0.0547576138				
Energy Not Supplied	:	ENS: =	5087.020 MWh/a				
Average Energy Not Supplied	:	AENS: =	0.789 MWh/Ca				

		DIGSILENT	Project:				
		PowerFactory	-----				
		14.0.524	Date: 3/4/2015				
Reliability Assessment							
-							
- Network, connectivity analysis							
Selection = Whole System							
Yes = Common mode	Yes = Independent second failures						
Yes = Busbars / terminals	Yes = Double earth faults						
Yes = Lines / cables	No = Maintenance						
Yes = Transformers							
Study Case: Study Case		Annex:	/ 1				
Load Interruptions	TCIT	TCIF	AID	LPENS	LPEIC	ACIF	ACIT
Name	Ch/a	C/a	h	MWh/a	\$/a	1/a	h/a
LV load 2	913133.85	90794.54	10.06	1000.38	0.00	82.54	830.12
Low-Voltage Load	52894.45	5250.32	10.07	60.67	0.00	77.21	777.86
LV load 4	1115450.65	110720.02	10.07	1271.61	0.00	77.21	777.86
LV Load3	95250.77	9453.79	10.08	108.59	0.00	55.61	560.30
General Load 1	479.14	53.83	8.90	1197.85	0.00	53.83	479.14
LV load 1	68517.18	7698.23	8.90	72.60	0.00	53.83	479.14
LV load 7	168718.34	16754.36	10.07	182.22	0.00	31.55	317.74
General Load 3	317.74	31.55	10.07	95.32	0.00	31.55	317.74
LV load 6	376643.55	98229.70	3.83	406.78	0.00	73.86	283.19
Low-Voltage Load(1)	128071.28	2789.21	10.06	32.07	0.00	17.99	181.11
LV load 5	274736.32	27298.24	10.06	296.72	0.00	17.99	181.11
General Load 2	181.11	17.99	10.06	362.21	0.00	17.99	181.11

Reliability assessment Simulation result for the Base case (without DG)

		DIgSILENT	Project:
		PowerFactory	
		14.0.524	Date: 3/4/2015

Reliability Assessment
 -
 - Network, connectivity analysis

Selection = Whole System
 Yes = Common mode | Yes = Independent second failures
 Yes = Busbars / terminals | Yes = Double earth faults
 Yes = Lines / cables | No = Maintenance
 Yes = Transformers

Study Case: Study Case | Annex: / 1

System Summary

System Average Interruption Frequency Index : SAIFI: = 21.496565 1/Ca
 Customer Average Interruption Frequency Index : CAIFI: = 21.496565 1/Ca
 System Average Interruption Duration Index : SAIDI: = 213.721 h/Ca
 Customer Average Interruption Duration Index : CAIDI: = 9.942 h
 Average Service Availability Index : ASAI: = 0.9756025912
 Average Service Unavailability Index : ASUI: = 0.0243974088
 Energy Not Supplied : ENS: = 2001.061 MWh/a
 Average Energy Not Supplied : AENS: = 0.310 MWh/Ca

		DIgSILENT	Project:
		PowerFactory	
		14.0.524	Date: 3/4/2015

Reliability Assessment
 -
 - Network, connectivity analysis

Selection = Whole System
 Yes = Common mode | Yes = Independent second failures
 Yes = Busbars / terminals | Yes = Double earth faults
 Yes = Lines / cables | No = Maintenance
 Yes = Transformers

Study Case: Study Case | Annex: / 1

Load Interruptions Name	TCIT Ch/a	TCIF C/a	AID h	LPENS MWh/a	LPEIC \$/a	ACIF 1/a	ACIT h/a
LV load 2	913133.85	90794.54	10.06	1000.38	0.00	82.54	830.12
LV load 1	118503.28	3094.04	5.98	19.61	0.00	21.64	129.39
General Load 1	129.39	21.64	5.98	323.48	0.00	21.64	129.39
LV load 6	133000.00	13300.00	10.00	143.64	0.00	10.00	100.00
LV Load3	116971.59	1766.32	9.61	19.35	0.00	10.39	99.83
LV load 4	129060.00	12906.00	10.00	147.13	0.00	9.00	90.00
Low-Voltage Load	6120.00	612.00	10.00	7.02	0.00	9.00	90.00
LV load 7	144604.00	4460.40	10.00	48.17	0.00	8.40	84.00
General Load 3	84.00	8.40	10.00	25.20	0.00	8.40	84.00
LV load 5	106190.00	10619.00	10.00	114.69	0.00	7.00	70.00
General Load 2	70.00	7.00	10.00	140.00	0.00	7.00	70.00
Low-Voltage Load(1)	110850.00	1085.00	10.00	12.40	0.00	7.00	70.00

Reliability Assessment				
- Network, connectivity analysis				
Selection = Whole System				
Yes = Common mode		Yes = Independent second failures		
Yes = Busbars / terminals		Yes = Double earth faults		
Yes = Lines / cables		No = Maintenance		
Yes = Transformers				
Study Case: Study Case		Annex:		/ 1
Buses Name		AIT h/a	AIF 1/a	AID h
SingleBusbar(3)	/SB 2	830.12	82.54	10.06
	Terminal(2)	830.12	82.54	10.06
	Terminal(1)	129.39	21.64	5.98
SingleBusbar(2)	/SB1	129.39	21.64	5.98
SingleBusbar(6)	/SB 6	100.00	10.00	10.00
	Terminal(6)	100.00	10.00	10.00
SingleBusbar(9)	/SB 3	99.83	10.39	9.61
	Terminal(3)	99.83	10.39	9.61
SingleBusbar(4)	/SB 4	90.00	9.00	10.00
	Terminal(4)	90.00	9.00	10.00
	Terminal	90.00	9.00	10.00
SingleBusbar(7)	/SB 7	84.00	8.40	10.00
	Terminal(7)	84.00	8.40	10.00
SingleBusbar(5)	/SB 5	70.00	7.00	10.00
	Terminal(5)	70.00	7.00	10.00
	Terminal(8)	70.00	7.00	10.00
SingleBusbar	/132 KV	0.00	0.00	0.00
SingleBusbar(1)	/15 KV	0.00	0.00	0.00

Figure D.2 reliability assessment simulation result after DG integration