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THESIS NO :

IMPACT OF DISTRIBUTED GENERATION ON DISTRIBUTION NETWORK LOSSES AND VOLTAGE PROFILE

by

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TABLE OF CONTENTS

ACKNOWLEDGMENTS……………………………………………………………….i
TABLE OF CONTENTS……………………………………………………………ii
LIST OF FIGURES………………………………………………………………….v
LIST OF TABLES…………………………………………………………………vi
ABSTRACT………………………………………………………………………. vii
LIST OF ABBREVIATIONS……………………………………………………..viii
LIST OF SYMBOLS………………………………………………………………..ix
CHAPTER 1 INTRODUCTION…………………………………………………….1
1.1 Introduction to Distributed Generation………………………………………..1
1.2 Traditional Concept of Power Systems…………………………………………3
1.3 New Concept of Power Systems……………………………………………...4
1.4 Benefits and Drawbacks of Distributed Generation………………………………..5
1.5 Applications of Distributed Generation ……………………………………... 7
1.6 Problem Statement………………………………………………………… 8
1.7 Thesis Objectives…………………………………………………...…...8
1.8 Project Scopes and Limitations……………………………………………....9

CHAPTER 2 LITERATURE REVIEW……………………………………………10
2.1 Distributed Generation Resources……….……………………………….…………10
2.2 Integration with the Grid……………………….…………………………13
2.3 Distributed Generation, a Key to the Future of Electric System……………….....14
2.4 Impact of Distributed Generation…….……………………………………...14
2.5 Voltage Impact……………………………………………………………….15
2.6 Losses……………………………………………………………………...16
2.7 Protection Needs…………………………………………………………......18
2.8 Reverse Power or Backfeed Protection…………………………………...……18

CHAPTER 3 RESEARCH METHODOLOGY…..…………………..………………..19

3.1 Research Scope…………………………………………………………………19
3.2 Tasks…………………………………………………………………………19
3.3 Procedure….…………………………………………………………………21

CHAPTER 4 RESULTS AND DISCUSSION..……………………………………...23
4.1 IEEE 34 Node Feeder Analysis…………………………………………...23
4.1.1 Description of IEEE 34 Node Test Feeder………………………………..23
4.1.2 Modeling of IEEE 34 Node Test Feeder…………………………………24
4.1.3 Load Flow…………………………………………...…………….…...26
4.1.4 Scenario Description…………………………………………………... 27
4.1.5 Voltage Analysis……………………………………………………………30
(a) Scenario 1: DG at Node 890……………………………………………...30
(b) Scenario 2: DG at Node 852……………………………………………...31
(c) Scenario 3: Impact of Sitting…………………………………………….. 32
(d) Summary…………………………………………………………………… 33
4.1.6 System Loss Analysis…………………………………………………. 34
(a) Scenario 1: DG at Node 890……………………………………………...34
(b) Scenario 2: DG at Node 852…………………………………………….. 35
(c) Scenario 3: Impact of Sitting……………………………………………..36
(d) Summary……………………………………………………………………37
4.2 Nagarkot Feeder Analysis………………………………………………...37
4.2.1 Circuit Description…………………………………………………….…..37
4.2.2 One Line Diagram……………………………………………………...38
4.2.3 Scenario Description…………………………………………………...38
4.2.4 Voltage Analysis……………………………………………………………42
(a) Scenario 1: Small Scale DG…………………………………………... 42
(b) Scenario 2: Large Scale DG…………………………………………... 42
(c) Scenario 3: Distributed Location Impact…………………………………43
(d) Summary……………………………………………………………………44
4.2.5 System Loss Analysis…………………………………………………. 45

(a) Scenario 1: Small Scale DG…………………………………………….... 45
(b) Scenario 2: Large Scale DG…………………………………………….... 46
(c) Scenario 3: Distributed Location Impact…………………………………47
(d) Summary…………………………………………………………………48

CHAPTER 5 CONCLUSIONS AND RECOMENDATIONS……………………….50
5.1 Conclusions…………………………………………………………………50
5.2 Recommendations………………………………………………………....50

REFERENCES…………………………………………………………………..51
PUBLICATION……………………………………………………...……….55
APPENDIX……………………………………………………………………...56

LIST OF FIGURES

Figure 1.1 DER Placement in Power System………………………………………. 2

Figure 1.2 Traditional Industrial Concept of the Electrical Energy Supply……………4

Figure 1.3 New Industrial Concept of the Electrical Energy Supply…………………. 5

Figure 1.4 Island Operation………………………………………………………….7

Figure 1.5 DG Parallel to the Main Grid……………………………………………..8

Figure 3.1 Block diagram of Summary of Activities to be Carried Out……………...20

Figure 4.1 IEEE 34 Node Test Feeder……………………………………………….. 23

Figure 4.2 DIgSILENT Power Factory Model of IEEE 34 Node Test Feeder……….25

Figure 4.3 DG at Lowest Voltage Location, Node 890……………………………… 28

Figure 4.4 DG at Node 852…………………………………………………………...29

Figure 4.5 DG at Laterals, IEEE 34 Node…………………………………………… 30

Figure 4.6 Voltage Profile, DG at Node 890………………………………………… 31

Figure 4.7 Voltage Profile, DG at Node 852………………………………………… 32

Figure 4.8 Voltage Profile, Impact of Sitting, IEEE 34 Node……………………….. 33

Figure 4.9 System Losses, Scenario 1, IEEE 34 Node………………………………..35

Figure 4.10 System Losses, Scenario 2, IEEE 34 Node………………………………35

Figure 4.11 System Losses, Scenario 3, IEEE 34 Node………………………………36

Figure 4.12 Single Line Diagram, Nagarkot feeder…………………………………..38

Figure 4.13 Lowest Voltage Location, Nagarkot feeder……………………………...39

Figure 4.14 Five Distributed Locations, Nagarkot feeder……………………………41

Figure 4.15 Ten Distributed Locations, Nagarkot feeder…………………………… 41

Figure 4.16 Voltage Profile Comparison, Scenario 1, Nagarkot feeder………………42

Figure 4.17 Voltage Profile Comparison, Scenario 2, Nagarkot feeder………………43

Figure 4.18 Voltage Profile Comparison, Scenario 3, Nagarkot feeder………………44

Figure 4.19 System Losses, Scenario 1, Nagarkot feeder……………………………46

Figure 4.20 System Losses, Comparison, Scenario 2, Nagarkot feeder……………... 46

Figure 4.21 System Losses, Comparison, Scenario 3, Nagarkot feeder……………... 48

LIST OF TABLES

Table 2.1 Distributed Generation Projects…………………….………………………... 11
Table 4.1 Comparison: IEEE result and DIgSILENT Result, IEEE 34 Node……….. 25
Table 4.2 Voltage at Node 890 after Integrating DG…………………………………33
Table 4.3 System Loss Comparison, IEEE 34 Node………………………………… 37
Table 4.4 Lowest Voltage after Integrating DG, Nagarkot Feeder…………………...44
Table 4.5 System Losses Comparison, Nagarkot Feeder……………………………..48

ABSTRACT

This research elaborates the impacts of installing DG on a distribution circuit. The work is focused on analyzing the impact of DG installation on distribution network operation including voltage analysis and electric losses of the system. Different DG penetration levels, locations and the impacts of installing one large-scale DG on the main distribution line and distributing it several locations on voltage profile and losses are explored. IEEE 34 node test feeder and Nagarkot feeder of Bhaktapur distribution system was built using its one-line diagram in DIgSILENT PowerFactory 2017 to perform detailed analysis.

The research analyses several case studies that explains the impacts of installing distributed generation (DG) on a distribution network operation including the voltage profile and losses of the system. Wind Turbine Generators are introduced as Distributed Generators (DGs) at various nodes and the impacts that DG produces on power losses and voltage profile is studied. Simulated results obtained using load flow are presented and discussed.

Research findings include:

• Distributing DG at several locations along the distribution feeder can provide better voltage improvement and losses reduction than installation of aggregated DG of the same size at one location.

• DG implementation as a source of active power has a great positive impact on improving the voltage profile and losses through the entire distribution network.

• The losses of the system vary as the DG output changes. In general, the minimum losses occur when the size of the DG is equal to the feeder load which is distributed at several locations. However, it can vary depending on the characteristics of the feeder.

LIST OF ABBREVIATIONS

ANSI	American National Standards Institute
CHP	Combined Head and Power
CIGRE	The Council on Large Electric Systems (In English)
DER	Distributed Energy Resources
DG	Distributed Generation
DGR	Distributed Generation Resource
EIA	Energy of Information Technology
EPS	Electric Power System
HV	High Voltage
IEEE	Institute of Electrical and Electronics Engineers
kV	Kilo Volt
kW	Kilo Watt
LTC	Load Tap Changer
LV	Low Voltage
MV	Medium Voltage
MVA	Megavolt Amperes
Mvar	Mega Volt Ampere Reactive
MW	Mega Watt
OPF	Optimal Power Flow
PU	Per Unit
PV	Photovoltaic
UK	United Kingdom
WTG	Wind Turbine Generator

LIST OF SYMBOLS

&	And
=	Is Equal To
<	Less Than
%	Percentage
+	Plus
P	Active Power
Q	Reactive Power
V	Voltage
W	Watt

CHAPTER ONE: INTRODUCTION

1.1 Introduction to Distributed Generation

Distributed generation (DG) is an approach that employs small scale technologies to generate electric power near the end users or load centers. Distributed Generation/DG technologies typically contain standard generators, and that they offer various potential benefits. In most of the cases and as per the research of Intelligent Energy Europe (Dec 2006), distributed generations provides lower-cost per unit electricity, higher power reliability, quality power, less disturbance and security with fewer environmental consequences compared to traditional power generation and transmission. The power electricity market is undergoing amazing transformation due to the competitive surrounding. The 'growing pains' of this huge transformation including losses, value 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.

As the approach used in the traditional electric power paradigm, generally large-scale generating stations are place at distant from the load centres bearing large transmission and distribution losses whereas DG systems employ various, but small plants and can give power onsite with very little reliance on the distribution and transmission grid. DG technologies yield power in capacities that vary from a fraction of a power unit (Kw) upto one hundred of megawatts (MW) as per the Linden et. Al, IEA. The term Distributed Energy Resources (DER) refers to DG along with storage technologies such as batteries. DG can be interconnected at different load levels (substation, distribution feeder or customer) as shown in Figure 1.1.

The centralized generation remains the primary source of electricity whereas the DER provides dependability, resilience and transmission & distribution grades to the grid. Large power plants area unit capital-intensive and need transmission and distribution grids to provide the power supply.

The technologies for DG are based on reciprocating engines, photovoltaic, fuel cells, combustion gas turbines, micro turbines and wind turbines. The technologies are referred as an alternate energy system as they supply an alternate to the traditional energy sources i.e. oil, gas, coal, water etc and can even be used to enhance the present electrical system. DGs are getting more and more popular because of their low emission, low noise levels and high efficiency.

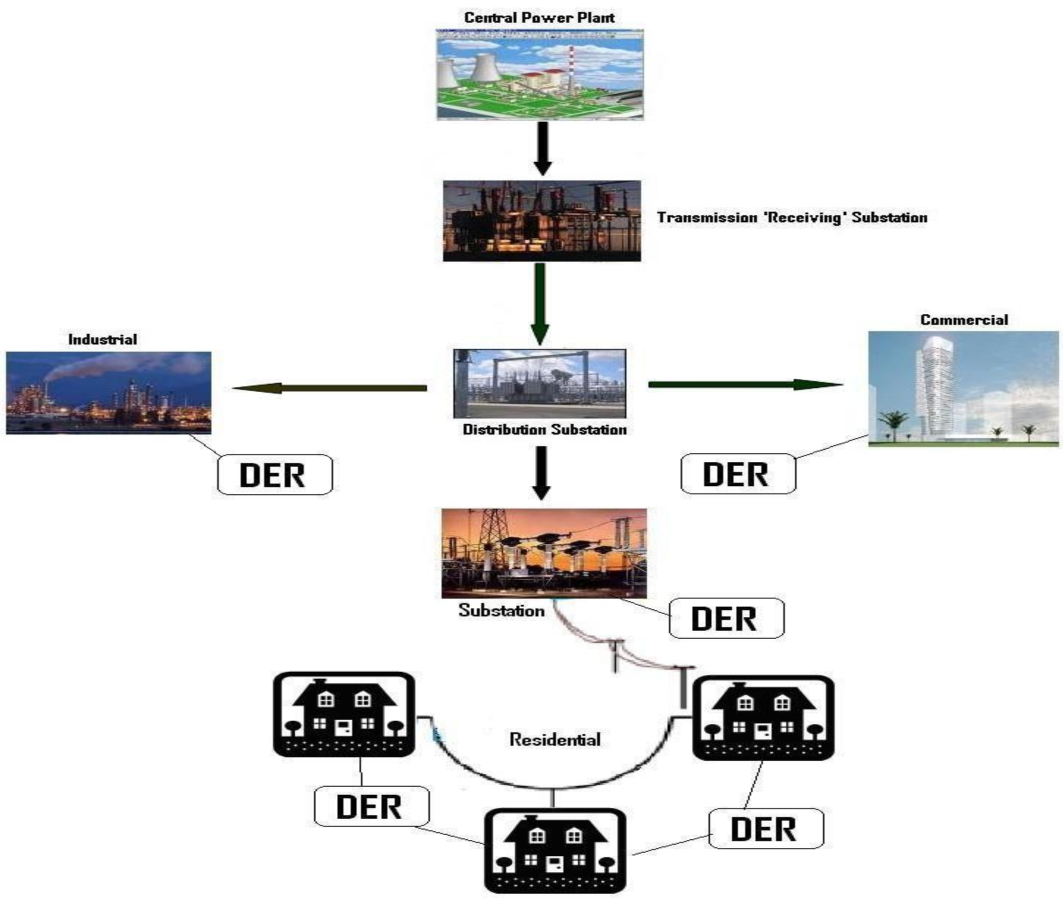


Fig. 1.1 DER placements in power system (Source: India Smart Grid Forum)

One of the main advantages of DG is their close proximity to the customer loads they are serving. DG will play a very important role in improving the dependableness of the present grid, reducing the losses, providing voltage support and improving power quality.

The major obstacle for the distributed generation has been the high cost for installation. However, the costs have decreased significantly over the past 20 years (Japan Smart Community Allaince, August 29, 2014).

1.2 Traditional Concept of Power Systems

Currently, most of the power systems generates and provides electricity having the subsequent considerations:

● Electricity generation is produced in large power plants, usually located close to the primary energy source (for instance: coil mines) and far away from the consumer centre's.

● Electricity is transmitted and distributed to the customers using a large passive distribution network, which involves high voltage (HV), medium voltage and low voltage.

● These distribution networks are designed to operate radially. The power flows solely in one direction up to consumers or end users via high voltage, medium voltage and low voltage on the radial distribution networks or feeders.

● In this process, there are three stages to be passed through before the power reaching the final user, i.e. generation, transmission and distribution.

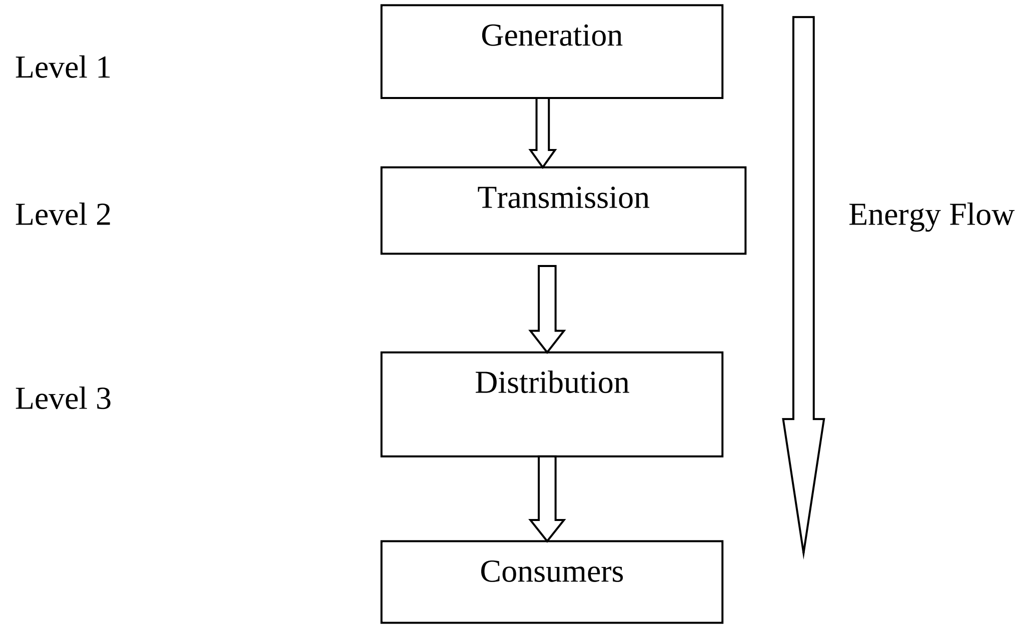


Fig. 1.2 Traditional industrial conception of the electrical energy supply

In the first stage the electricity is generated in large generation plants, located in no populated areas away from loads to get round with the economics of size and environmental issues. Second stage is accomplished with the support of various equipment such as transformers, overhead transmission lines and underground cables. The last stage is the distribution of power that links the utility system and the end customers. This stage is the most important part of the power system, as the final power quality depends on its reliability.

The electricity demand is increasing continuously. Consequently, electricity generation must increase in order to meet the demand requirements. Traditional power systems face this growth, installing new support systems in level 1 (figure 1.2). Whilst, addition in the transmission and distribution levels are less frequent.

1.3 New Concept of Power Systems

Nowadays, the technological evolution, environmental policies, and also the expansion of the finance and electrical markets, are promoting new conditions in the sector of the electricity generation.

New DG technologies allow the electricity to be generated in small sized plants near the end user customer. Moreover, the increasing use of renewable sources in order to reduce the environmental impact of power generation leads to the development and application of new electrical energy supply schemes.

In this new conception, the generation is not exclusive to level 1. Hence some of the energy-demand is supplied by the centralized generation and another part is produced by distributed generation. The electricity is going to be produced closer to the users.

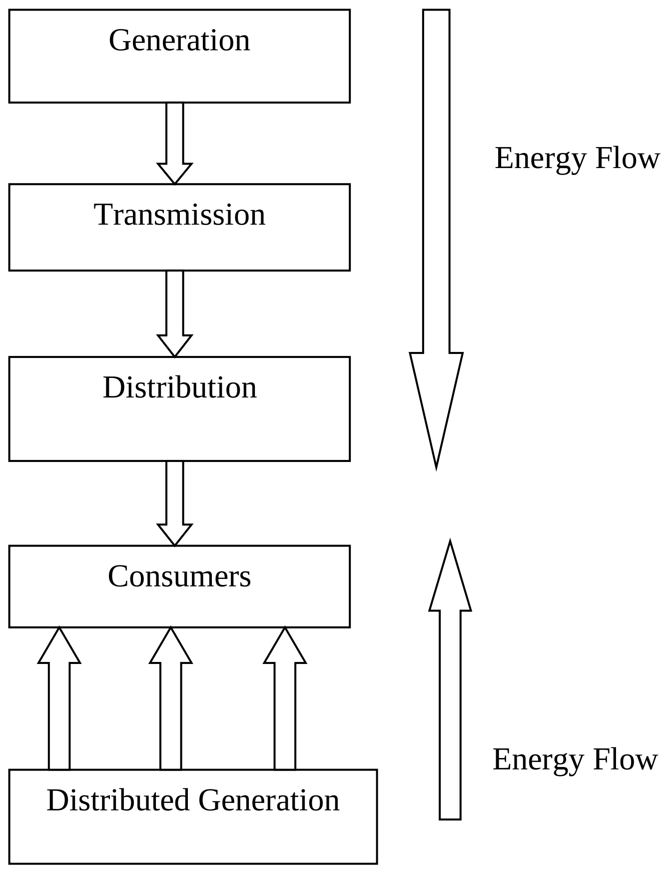


Fig. 1.3 New industrial concept of the electrical energy supply

1.4 Benefits and Drawbacks of Distributed Generation

Large scale integration of distributed generators at the distribution network is at present, the trend followed in power systems to supply some loads or demands. These generators are of considerable smaller size than the traditional existing generators (thermal, nuclear, etc…). An overview of some common benefits and drawbacks of the DG are presented below:

1) Benefits

- Connection of DG is intended to increase the reliability of power supply provided to the customers, using local sources, and if possible, reduce the losses of the transmission and distribution systems.
- The connection of DG to the power system could improve the voltage profile, power quality and support voltage stability. Therefore, the system can withstand higher loading situations.
- The installation of DG takes less time and payback period. Many countries encourage and subsidize the development of renewable energy projects through a portfolio obligation and green power certificates. This incentives investment in small generation plants.
- Some DG technologies have low pollution and good overall efficiencies like combined heat and power (CHP) and micro-turbines.

2) Drawbacks

- DGs are connected to the grid via power converters, which injects harmonics into the system (Thong et.al.,).
- The connection of DG may lead to over-voltage, interruption, fluctuation and unbalance of the system voltage if coordination with the utility supply is not properly achieved.
- Depending on the network configuration, the penetration level and the nature of the DG technology, the power injection of DG may increase the power losses in the distribution system (Favuzza, S., et al., 2007)
- Short circuit levels are changed when a DG is connected to the network. Therefore, relay settings should be changed and if there is a disconnection of DG, relay should be changed back to its previous state.

1.5 Applications of Distributed Generation

The power system is prone to failures and disturbances due to weather related issues, accidents, human errors etc. Having the DG as a backup source ensures the reliability of power supply which is critical to business and industry. The overall reliability of the system can be improved. DG can be used to continuous supply to some of the load feeders using switch operations. As shown in figure 1.4, a fault occurs on feeder 2, but continuous power can be supplied to load points B and C through DG in the form of an island. Such an operation is termed as islanded mode.

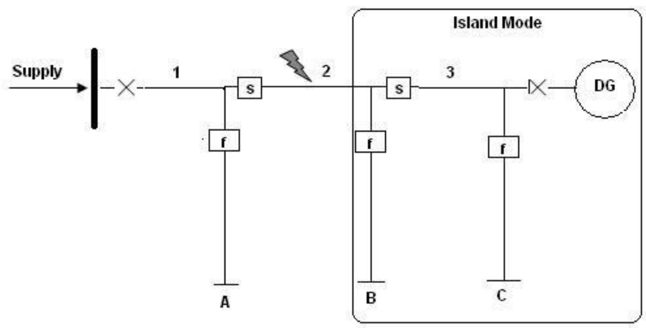


Fig. 1.4 Island Operation

Another key DG application is that it can also be used in parallel to the main grid as a support for the loads and also by injecting excess power back to the grid network when the DG capacity or production is more than the required feeder demand. The DG can help the main grid during peak load hours when the feeder capacity is not enough to meet the demands of the customers. The load shedding can be avoided by having a DG support. The DG helps peak shaving as shown in figure 1.4 that reduces the customer electric bills and also improves the reliability of the system.

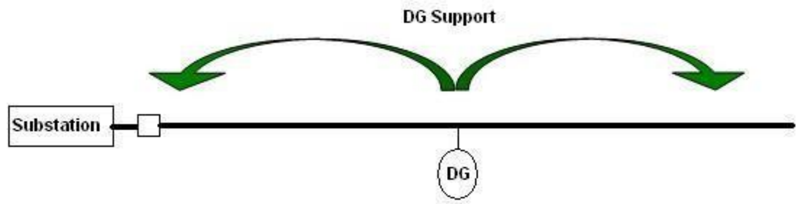


Fig: 1.5 DG parallel to the Main Grid

The DG can be used as a standby for consumers that cannot tolerate interruption of service e.g. hospitals. The DG can also be used as a stand-alone to supply power to the customers that are not connected to the grid. For example, the DG can be used as stand-alone in remote areas where cost of connecting to the main grid is too high.

1.6 Problem Statement

One of the greatest and the most obvious problem that Nepal and the other developing countries are facing today is the increasing demand of electricity and its poor supply. The rising gap between demand and supply of electricity is the major factor of concern to developing countries like Nepal. At the mean time, customers often suffer from poor power quality such as variations in voltage or electrical flow that results from a various factors, including poor switching operations in the network, voltage dips, interruptions, transients, and network disturbances from loads and many others. The electric distribution system that feeds the city is susceptible to outage. An assessment of potential for alternative energy technologies to improve reliability and deliverability of electric power to the city is a must. It is not possible to provide reliable electricity supply to the consumers by only normal central power generation technology. Electricity generation should be deregulated meaning that there should be distributed generation by making use of renewable energy technology.

1.7 Thesis Objectives

The main objective of this research is to find out the impacts of different DG penetration levels at one and several distributed locations on the voltage profile and losses of the distribution system.

The specific objectives are:

- To identify the voltage profile and loss of IEEE 34 Node Test Feeder after DG injection.
- To identify the voltage profile and loss of Nagarkot Feeder after DG injection.
- To identify the suitable location to inject DG.

1.8 Project Scopes and Limitations

- To analyse the impact of system losses and voltage profile when DG is applied in the existing system. The system develop in this thesis has been limited to IEEE 34 node feeder and Nagarkot feeder of Bhaktapur distribution system only.
- The DGs installed on the system produce real power only. Injecting Reactive Power (Q) using power electronic converters may cause over-voltages and will not improve the power factor at the load levels. The DG technologies have been limited to wind turbines generator (WTG) in this research.
- Models have been developed in DIgSILENT PowerFactory 2017.

CHAPTER TWO: LITERATURE REVIEW

2.1 Distributed Generation Resources

Conventional power stations, such as coal-fired, gas and nuclear powered plants, as well as hydroelectric dams and large-scale solar power stations are centralized and often require electric energy to be transmitted over long distances (Abdel-Ghany, *et al.*, 2015). By contrast, distributed energy resources systems are decentralized, modular and more flexible technologies, which are located close to the load they serve, albeit having capacities of only 10 megawatts (MW) or less. These systems can comprise multiple generation and storage components (Singh, 2017).

Distributed energy resources (DER) typically use renewable energy sources, including small hydro, biomass, biogas, solar power, wind power, and geothermal power, and increasingly play an important role for the electric power distribution system. A grid-connected device for electricity storage can also be classified as a DER system, and is often called a distributed energy storage system (Choudhary, *et al.*, 2015). By means of an interface, DER systems can be managed and coordinated within a smart grid. Distributed generation and storage enables collection of energy from many sources and may lower environmental impacts and improve security of supply.

Distributed Generation (DG) is an approach that employs small-scale technologies to produce electricity close to the end users of power. DG technologies often consist of modular renewable energy generators, which have a number of benefits such as lowering the cost of electricity, and increasing the reliability and security of power supply with fewer social and environmental consequences. Moreover, DG sources can use islanding techniques to serve the local distribution network even when the central grid is offline due to outages or load shedding (National Planning Commission; NEA Engineering Company, 2018).

The fundamental concept of bi-directional planning and implementation for Sustainable Distributed Generation and Grid Access to All (SUDIGGAA) is that it has to work on both transmission and distribution sides of the power system. On distribution, at the local level, locating a substation that best serves the local distribution network plan and constructing generation projects to feed the network; and on transmission, on the part of the central grid, constructing radial network expansion targeted and homing towards the substations at the local municipalities.(National Planning Commission; NEA Engineering Company, 2018). National Planning Commission, Nepal proposed a plan for sustainable distributed generation and grid access to all by 2022 as shown in Table 2.1(National Planning Commission; NEA Engineering Company, 2018).

Table 2.1 : Distributed Generation projects

Distributed Generation projects	**Nos**
Hydropower	221
Solar PV	481
Biomass to Electricity	50
Wind Power	1

2.1.1 Solar Power

Photovoltaics, by far the most important solar technology for distributed generation of solar power, uses solar cells assembled into solar panels to convert sunlight into electricity. It is a fast-growing technology doubling its worldwide installed capacity every couple of years (Adhikari, 2013). PV systems range from distributed, residential, and commercial rooftop or building integrated installations, to large, centralized utility-scale photovoltaic power stations.

2.1.2 Wind Power

Wind power is the use of air flow through wind turbines to provide the mechanical power to turn electric generators and traditionally to do other work, like milling or pumping. Wind power, as an alternative to burning fossil fuels, is plentiful, renewable, widely distributed, clean, produces no greenhouse gas emissions during operation, consumes no water, and uses little land. Wind turbines can be distributed energy resources, they can be built at utility scale, or they can be a combination of both. These have low maintenance and low pollution, but distributed wind unlike utility-scale wind has much higher costs than other sources of energy when purchased as a capital expenditure (Najy, *et al.*, Review).

2.1.3 Small Hydro Power

Kinetic energy turbines can be deployed in arrays to serve the needs on a residential, commercial, industrial, municipal or even regional scale. Micro-hydro kinetic generators neither require dams nor impoundments, as they utilize the kinetic energy of water motion, either waves or flow.

2.1.4 Waste-to-Energy

Municipal solid waste and natural waste, such as sewage sludge, food waste and animal manure will decompose and discharge methane-containing gas that can be collected and used as fuel in gas turbines or micro turbines to produce electricity as a distributed energy resource. Additionally, a California-based company, Gate 5 Energy Partners, Inc. has developed a process that transforms natural waste materials, such as sewage sludge, into biofuel that can be combusted to power a steam turbine that produces power (Zayandehroodi, *et al.*, 2012). This power can be used in lieu of grid-power at the waste source (such as a treatment plant, farm or dairy).

2.1.5 Energy storage

A distributed energy resource is not limited to the generation of electricity but may also include a device to store distributed energy. Distributed energy storage systems applications include several types of battery, pumped hydro, compressed air, and thermal energy storage. Some technologies provide short-term energy storage, while others can sustain for much longer. Bulk energy storage is presently dominated by hydropower dams, both conventional as well as pumped.

2.1.6 Vehicle-to-Grid

Future generations of electric vehicles (EVs) may have the ability to deliver power from the battery in a vehicle-to-grid into the grid when needed. An electric vehicle network has the potential to serve as a distributed energy storage systems (Jeff Mackinnon, 2015).Vehicle to grid storage capabilities can also enable EVs to store and discharge electricity generated from renewable energy sources such as solar and wind, with output that fluctuates depending on climate and time of day.

2.2 Integration with the grid

For reasons of reliability, distributed generation resources would be interconnected to the same transmission grid as central stations. Various technical and economic issues occur in the integration of these resources into a grid. Technical problems arise in the areas of power quality, voltage stability, harmonics, reliability, protection, and control. Behavior of protective devices on the grid must be examined for all combinations of distributed and central station generation (Choudhary, *et al.,* 2015). A large scale deployment of distributed generation may affect grid-wide functions such as frequency control and allocation of reserves. As a result, smart grid functions, virtual power plants and grid energy storage such as power to gas stations are added to the grid.

Each distributed generation resource has its own integration issues. Solar PV and wind power both have intermittent and unpredictable generation, so they create many stability issues for voltage and frequency (Adhikari, 2013). These voltage issues affect mechanical grid equipment, such as load tap changers, which respond too often and wear out much more quickly than utilities anticipated. Also, without any form of energy storage during times of high solar generation, companies must rapidly increase generation around the time of sunset to compensate for the loss of solar generation. This high ramp rate produces what the industry terms the duck curve that is a major concern for grid operators in the future. Storage can fix these issues if it can be implemented. Flywheels have shown to provide excellent frequency regulation.ve and prevent generator use fluctuation and can help to maintain voltage profile (Tuitemwong & Premrudeepreechacharn, 2011).

However, cost is a major limiting factor for energy storage as each technique is prohibitively expensive to produce at scale and comparatively not energy dense compared to liquid fossil fuels. The penetration level of DGs in radial distribution network has a significant impact on power flow, harmonics, voltage regulation and short circuit levels of the Network (Huda & Živanović, 2017).

2.3 Distributed Generation (DG), a key to the future of Electric system

Distributed Generation has a key role to play in the future of electricity. The EIA (Energy of Information Administration) provides statistics and data analysis about the growing demand of electricity and the role of DG. Distributed Generation provide great potential to offset traditional utility investments in generation and transmission facilities. EIA (Energy in Brief) presents the report based on facts and figures of supply, demand and electricity markets which shows that DG's contribution to electricity is predicted to increase drastically and renewable-generated electricity will account for 12.5% of total U.S. electricity generation in 2030. Many papers have gone through the importance of the distributed generation (DG) and its applications and benefits in enhancing the electrical system. The distributed generation has the potential to provide ancillary services with proper power electronic interface to the main grid (Joos G, IEEE, 2000).

2.4 Impact of Distributed Generation (DG)

Interconnecting a DG to the distribution feeder can have significant effects on the system such as power flow, voltage regulation, reliability etc. A DG installation is a change in traditional characteristics of the distribution system. Most of the distribution systems are designed such that the power flows in one direction which is the traditional concept. The installation of a DG introduces another power source in the system. When the DG power excess than the connected load, it sends power towards the direction of power flow and at some point between the DG and substation; the real power flow is zero due to back flow of power from DG. The rules are defined for power flow reversal, optimal DG placement for reduction of losses and the impacts of DG on over-current protection (Baghzouz Y, June 2006). Zero point analysis and rules for modeling of Distributed Generation interaction with the system is presented (Willis, 2000).

The standards for interconnecting distributed resources to the power system are a set of standards consisting of 6 parts [1547 series, IEEE]. The standards provide criteria and requirement for interconnecting distributed resources to the power system. IEEE 1547.1 defines the requirement for interconnecting equipment that connects the DG to the electric power system is presented. The IEEE 1547.2 provides technical details and application to understand the IEEE standard. The IEEE 1547.3 guide addresses engineering concerns of design, operation and integration of DG island systems. The IEEE 1547.6 standard focuses on criteria, test and requirements for interconnection distribution secondary network of area electric power system (Area EPS) with Local EPS having Distributed Resource generation.

2.5 Voltage Impact

The DG installations have the overall impact on voltage profile of the system. Inclusion of DG improves the feeder voltage of distribution networks in areas where voltage dip or blackouts are problem for utilities. The voltage issues related to the installation of DG on current electrical system have been discussed in several papers. The impact of DG on electric losses, voltage profile and reliability were discussed (Borges, 2003). The purpose is to find out the optimal DG allocation and sizing for minimal losses, proper voltage and reliability support. The paper analyzes impact of DG on voltage regulation and losses, as well as the voltage flicker and harmonics that can be caused by the DG (Barker, 2000). The paper also addresses DG impacts on short circuit levels and the islanding operation of DG.

However, the DG can also confuse the voltage regulator settings and can cause the voltage to deviate above or below the permissible range. The paper (Le, A.D.T, 2006) highlights simulation that uses a voltage control method for optimal power injection from DG. The impacts of distributed generation (DG) on voltage regulation by Load Tap

Changing (LTC) can cause under-voltages and over-voltages if proper LTC tap transformer controls are not applied (Chensong Dai, 2004).

Several papers have highlighted the control models for the efficient operation of DG. The author presented operation and control for DG installation. The paper presents a DG control model which improves the network voltage efficiently. The author (Kashem, M.A, 2004) addressed network issues when multiple DGs are included in the network. The paper presents analytical methods and solutions to develop design criteria for DG installation. A simple analytical method is used to estimate voltage profile for radial distribution system when placing DG units with specific active and reactive power generation (Dai, C, 2003). The author (Kim, T.E, 2001) presented voltage regulation coordination methods of DG in a distribution system. The approach helps to make use of controlling DGs reactive power based on its real power along with satisfying system voltage requirements.

The installation of DG units in the distribution feeders may cause overvoltage due to too much injection of active and reactive power. For instance, a small DG system sharing a common distribution transformer with several loads may increase the voltage on the secondary side, which is sufficient to cause high voltage at these customers (Barker, 2000). This can happen if the location of the distribution transformer is at a point on the feeder where the primary voltage is near or above the fixed limits; for instance: ANSI (American National Standards Institute) upper limit 126+ volts on a 120 volt base.

2.6 Losses

Installation of DG has its impact on the losses and power factor of the distribution system. A few papers have discussed about the reduction of losses by inserting power from DG into the system. The role of DG in loss reduction based on a power summation method is presented (Borges, 2003). The author (Barker, 2000) briefly presented the impact of DG on losses of the feeder. In this research, the loss analysis at different penetration levels of DG and distributing it across several locations are presented. A genetic optimization algorithm has been used in order to find the optimal location and size of different DG units in a radial distribution system (M.F. Kotb, 2010). Three constraints (voltage, active and reactive power losses and DG size) and the Newton-Raphson method have been used in an effort to reduce the total power losses and improve the voltage profile. Another analytical technique to calculate the optimum size and to allocate DG units in the optimum place has presented (M. Shaab, 2013) where the authors found that minimum losses with better voltage profile can be achieved with integrating one DG unit of optimum size and in an optimum location rather than integrating several DG units at several locations.

Load flow and short circuit studies have been conducted to analyse the impact of photovoltaic on distribution systems (K. Balamurugan, et al., 2012). DIgSILENT PowerFactory software has been used for the analysis. The authors found that the higher the penetration level resulted the higher the positive impact of DG in terms of power losses and voltage profile.

The optimum location of DG can be obtained using load flow analysis software, which is able to investigate the suitable location of DG within the system in order to reduce the losses. For example: if feeders have high losses, injecting a number of small capacity DGs will have an important positive effect on the losses and have a great benefit to the distribution system. On the other hand, if larger units are added, they must be installed considering the feeder capacity boundaries (barker, 2000). For example: the feeder capacity may be limited due to constraints of overhead lines and cables have thermal characteristic that cannot be exceed.

Most DG units are owned by the customers. The grid operators cannot decide the locations and sizing of the DG units. Normally, it is found that losses decrease when generation takes place closer to the load site. However, as it was mentioned, local increase in power flow in low voltage cables may have undesired consequences due to thermal characteristics (Vu Van Thong, 2005).

2.7 Protection Needs

Power flow in networks without Distributed Generation usually is unidirectional, from high voltage transmission networks to radial low voltage distribution networks. However, the growing numbers of distributed generators, operating in parallel with the existing grid, lead to bidirectional power flow, therefore requiring new or defined protection schemes. According to Ault et al, the new protection requirements can be grouped as generating unit protection, distribution network protection and interface protection. Over-current protection is usually done via fuses, breakers and reclosers since most of the distribution networks are constructed radially, opening and closing of one device is normally sufficient to clear a fault.

2.8 Reverse Power or Backfeed Protection

The DG interconnection vary from utility to utility, some of them don't allow the dispersed generator to feed or sell power to the grid. Many of the distributed generator installations are intended to reduce the consumption of power by peak shaving the demand and to ensure that the most critical loads keep running in the case of the fault. It is required that bidirectional protection is embedded in the interconnection protection relay to disconnect the DG section if the power flows to the utility or grid, triggering the reverse power condition and isolating the distributed generation.

CHAPTER THREE: RESEARCH METHODOLOGY

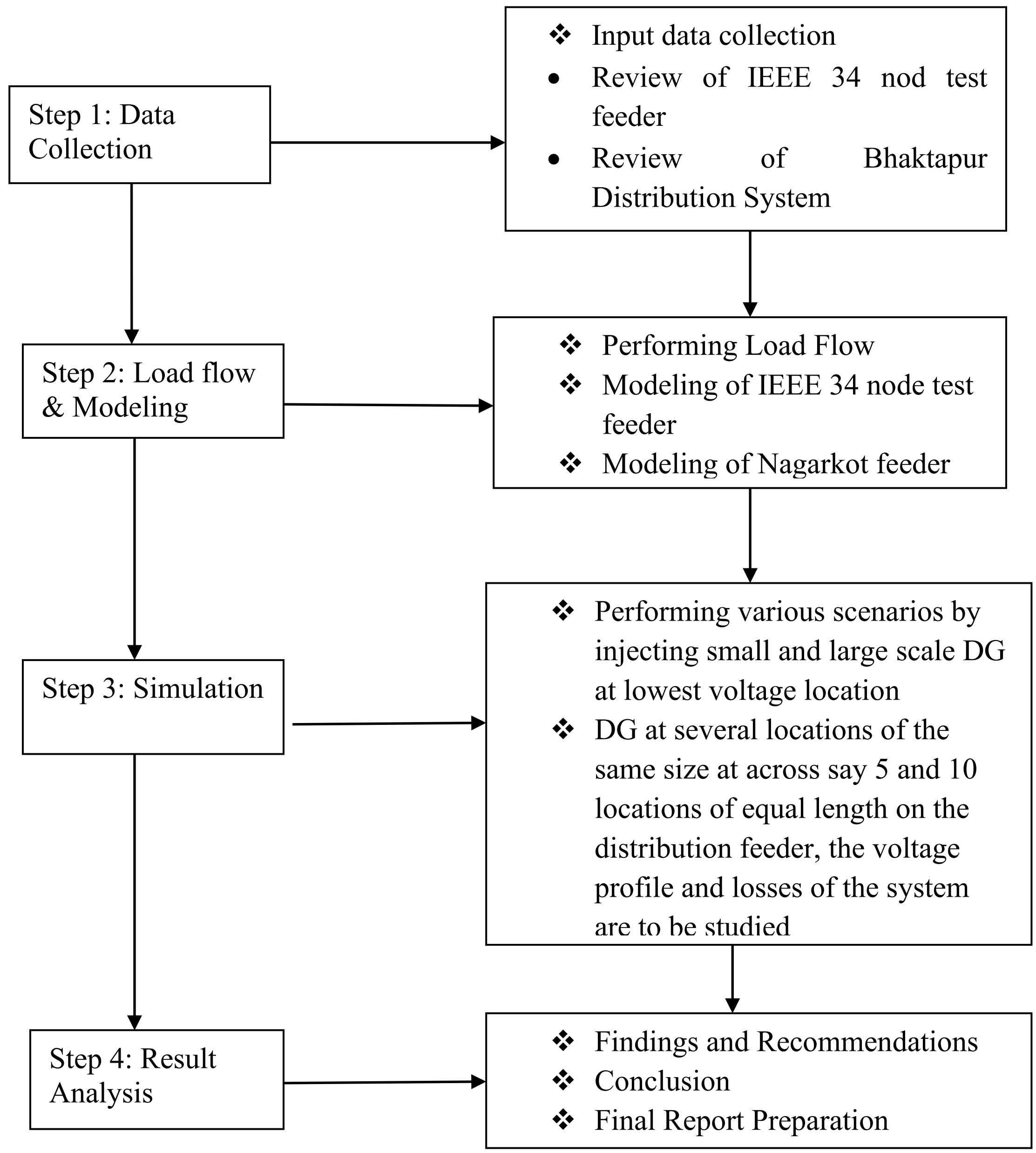
3.1 Research Scope

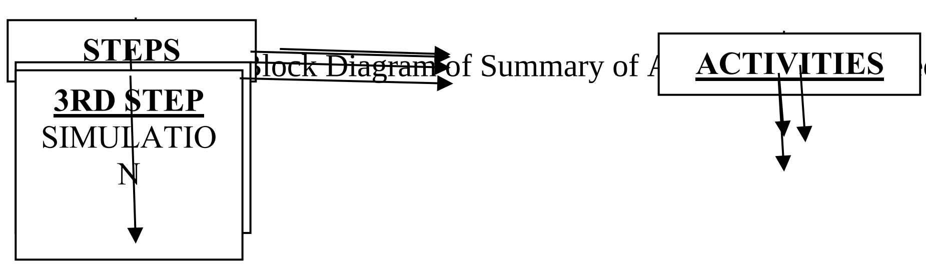
As the use of the distributed generation (DG) increase, it is critical to study its impacts on the power distribution system. The objective of this research is to explore the implications of installing distributed generation (DG) on a distribution feeder. The impacts focused in this research include voltage analysis and losses. The impact of distributed generation (DG) on system's voltage has been studied by injecting DG into an IEEE 34 node feeder and Nagarkot feeder of Bhaktapur distribution system. A loss analysis of the system when the DG is installed is also performed. The impacts of different DG penetration levels at one and several distributed locations on the voltage profile and losses are studied. The impacts of installing one large-scale DG on the distribution line vs. several small-scale distributed DGs of the same size are also explored and analyzed. Hence, key impacts of distributed generation on a distribution feeder are investigated in this research.

3.2 Tasks

The tasks performed for the research include:

1. Collecting data that include load on each feeder, feeder type (residential/commercial/industrial), number of houses/customers on each feeder, length of each section and distributor and transformer data.
2. Performing analysis on DIgSILENT PowerFactory. DIgSILENT PowerFactory is a power system analysis software for applications in generation, transmission, distribution and industrial systems.
3. Studying Impacts of DG on IEEE 34 node test feeder. The impacts focused in this research include voltage analysis and losses.
4. Performing voltage analysis on a distribution feeder based on different penetration levels of DG and distributing it across several locations along the selected feeder.
5. Analyzing losses of the selected system as the DG injects real power. The analysis is based on DG penetration, location, optimal sizing, impacts and large-scale aggregated and small-scale distributed DG comparison.





Block Diagram of Summary of A … d out

3.3 Procedure

On the comprehensive level, basically, there are four main phases used in analyzing the impacts of DG. They are as follows:

1. Data collection
2. Model building
3. Simulation
4. Result analysis

1. Data collection

The first step of methodology is collecting the required data necessary for the analysis. This includes the data such as load on each feeder, feeder type (residential/commercial/industrial), number of houses/customers on each feeder, length of each section and distributor, transformer data, loss data, conductor types etc.

2. Model building

The second steps of the methodology are Model Building, where the modeling of IEEE 34 node test feeder and Nagarkot feeder of Bhaktapur distribution system is carried out. DigSilent Power Factory is used as a power system simulator. It is a power simulator capable of modeling, analysis and simulation of complex power system models and scenarios. It has many functionalities from basic Power Flow Analysis, Fault Analysis, Voltage Stability Analysis, Load Flow Sensitivities, Contingency Analysis to advanced functionalities like Protection Functions, Distribution Network Optimization, Harmonic and Power Quality Analysis and Optimal Power Flow (OPF).

In the research, Transformers are modeled as load. Active power and power factor are specified. For Distributed Generation, only active power is input and the results are analyzed.

3. Simulation

Several simulations are carried out connecting each time a different size of DG along the distribution feeder at lowest voltage point recording each time the voltage profile and the active and reactive power losses. To illustrate the impact of various DG sizes, a small-scale DG of various sizes like DG Size 10%, 20%, 50%, 100% of the distribution transformer load and a large-scale DG of various sizes like 10%, 20%, 50%, 60%, 70% and 100% of the total feeder load is injected at lowest voltage locations in distribution feeder. Similarly, by distributing the DG at several locations of the same size at across say 5 and 10 locations of equal length on the distribution feeder, the voltage profile and losses of the system are studied.

4. Result Analysis

Based on the simulation done on the 3rd step, results are analyzed. The impacts of DG on losses and voltage profile for the selected system and interpret the result for different scenarios. Voltage Profile and Losses for two weakest node and at different nodes where laterals are branching out are analyzed. As per the methodology described above the block diagram used for the purpose of this thesis is shown below in figure 3.1

CHAPTER FOUR: RESULTS AND DISCUSSION

The distributed generation (DG) impact on system voltage is of critical importance. In a traditional distribution network, Load Tap transformers (LTC) are used to regulate the radial distribution circuits at substations. The line regulators at feeders and switched capacitor banks are also used to regulate voltage. The introduction of DG on a distribution network can interfere with the standard regulations. This section explores the impacts of injecting real power from the DG on a distribution network. Several case studies have been conducted to illustrate how different levels of DG penetration can impact voltage profile and losses of a distribution network of interest.

4.1 IEEE 34 Node Feeder analysis

4.1.1 Description of IEEE 34 node test feeder

The IEEE 34 node test feeder which is shown in figure 4.1 is an actual feeder located in Arizona characterized by long, lightly loaded, multiple three and single phase laterals and unbalanced distribution feeder having total load of 1769 kW and 1044 Mvar and two different operating voltages of 24.9 kV and 4.16 kV.

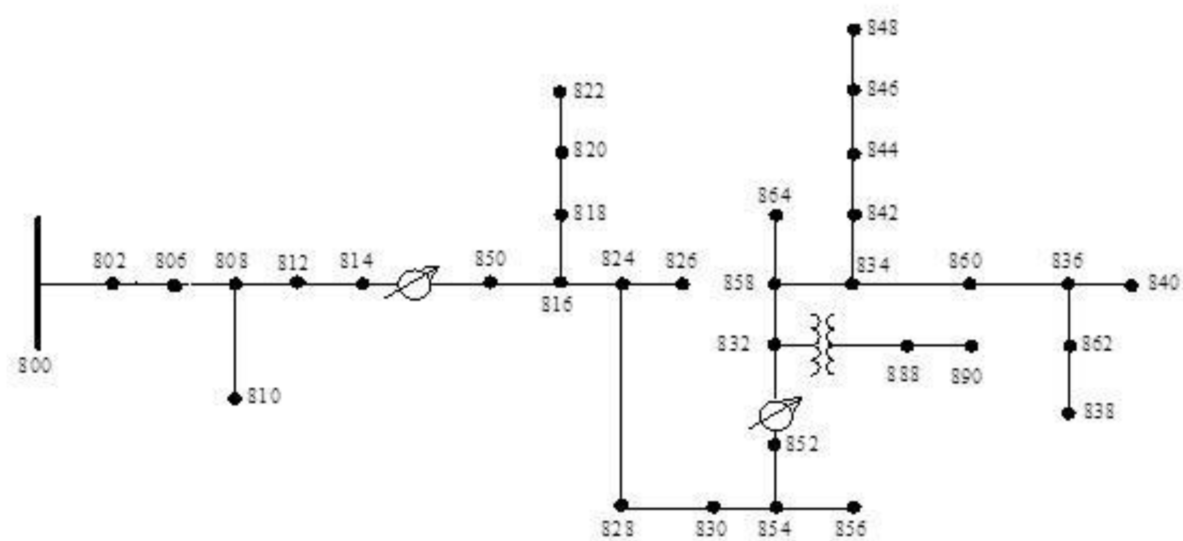


Fig 4.1 IEEE 34 node test feeder

The standard IEEE 34 Bus system's data can be get form the standard document (The Institute of Electrical and Electronics Engineers, Inc., n.d.) and according to this data The test feeder is modeled using the DIgSILENT Power Factory simulation package.

A Three phase autotransformer is used to simulate the voltage regulator. The external grid which is connected to the bus 800 is an infinite bus with 1.05 p.u. voltage and 20 MVA short circuit capacity. The Z & B matrices of the mentioned feeder in phase components are converted to sequence components using Eq. (i) and Eq. (ii) in order to enter the values in line type model of the feeders (K. Balamurugan, et al.,2012).

$Z_1=Z_2=Z_s-Z_m$ (i)

$Z_0=Z_s-2Z_m$ (ii)

Where,

$Zs = (Z_{aa}+Z_{bb}+Z_{cc})/3$ (iii)

$Z_m = (Z_{ab} + Z_{ac} + Z_{ba} + Z_{bc} + Z_{ca} + Z_{cb})/6$ (iv)

The terms used in the calculation of Zs are self-impedances and Zm are mutual impedances of phase a, b and c. Wind Turbine Generators (WTG) are used as distributed generators and only active power is injected as input.

4.1.2 Modelling of IEEE 34 node test feeder

The DIgSILENT model of IEEE 34 node feeder is shown in the figure 4.2 The IEEE 34 node test feeder has the following features reflecting the physical world:

1. Each section of the distribution system is modeled by actual phase impedance values.
2. The system includes single and two phase laterals.
3. Loads on each phase of each section are specified in real and reactive power
4. Distributed load models represent load on feeders with closely spaced load taps.
5. System includes voltage regulators and capacitive reactive power compensation.
6. The system has very long distributions lines and is lightly loaded.

7. There is also an in-line transformer for reducing voltage to 4.16 kV for a short section of the feeder.

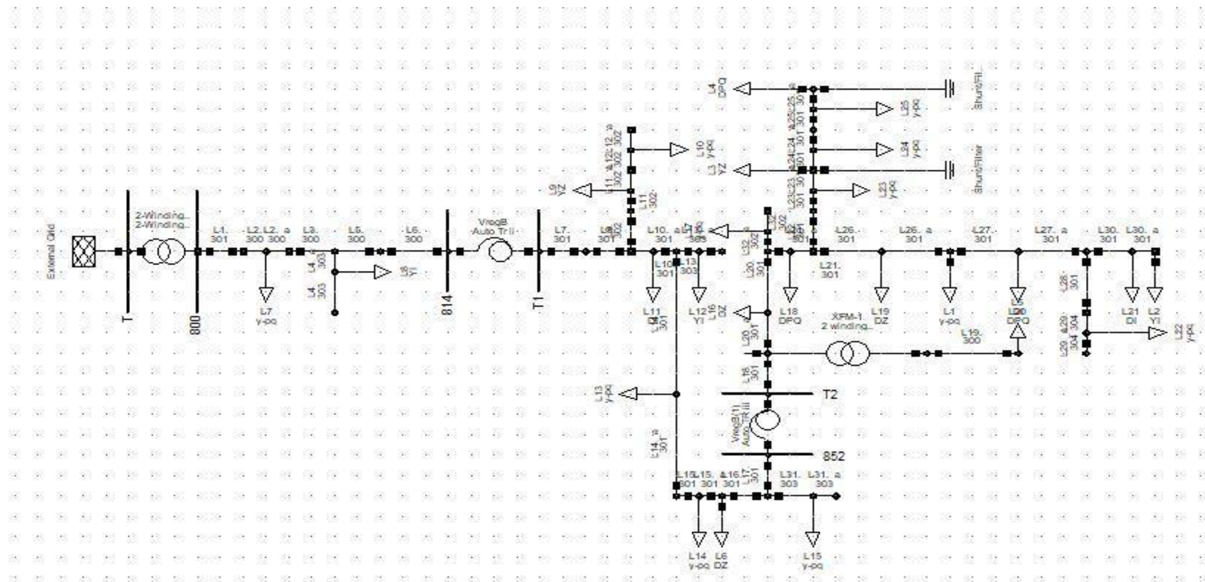


Fig 4.2 DIgSILENT PowerFactory Model of IEEE 34 node test feeder

The following assumptions are made during the modelling of IEEE 34 node test feeder:

1. The unbalanced phase loads in each three phase sections are summed up and taken as total three phase balanced loads.
2. The impedances for the main feeder are considered as only positive sequence impedances and all the loads were replaced by their equivalent balanced three phase loads.

The Power Factory results are summarized in Table 4.1 and are compared with IEEE system data.

Table 4.1 Comparison between IEEE results and PowerFactory results

Output Result	IEEE system data	PowerFactory	Difference (%)
kW Loss	273.04	270	-1.11

Minimum average voltage, p.u.	0.9193 at node 890	0.916 at node 890	-0.3589
Maximum average voltage, p.u.	1.05 at node 800	1.049 at node 800	-0.0952

However, the Kvar loss was found larger about 550 Kvar than the IEEE result which is 34.99 Kvar. The cause of large difference in the reactive power loss compared to the IEEE results for the no DG case is the substation transformer. This transformer was included in the DIgSILENT PowerFactory results, but it is excluded in the IEEE results. Also, Voltage regulator was modelled as three phase autotransformer which also contributes to this reactive power loss.

The authors presents the use of DIgSILENT PowerFactory's suitability for the integration of DG into distribution Networks (A. J. Owuor, et. al.., 2011). The authors have also modelled the IEEE 34 node test feeder in DIgSILENT PowerFactory and compares the base case IEEE phase voltage magnitudes with those obtained in the PowerFactory results. The maximum node voltage error for V_a, V_b, and V_c was 4.4%, 3.69% and 5.13% respectively. The authors also confirm that modelling results substantially agree with those of the IEEE Distribution Analysis Subcommittee.

In (Silva et.al...), the authors have also got the large reactive loss because they have also included the substation transformer in their analysis.

4.1.3 Load Flow

The verified IEEE bus is then tested in different condition of the electrical parameters. The detail unbalance Newton Raphson load flow study has been done in the research. The developed model is modified in order to analyze the behavior of the system with different loading condition. The load is varied in different nodes at different time frame and the data is observed from different branches. Thus obtained records are studied to obtain the behavior of the system at different loading condition.

In this study, transformers are modeled as load. Active power and power factor are specified. For Distributed Generation, only active power is input and the results are analyzed.

4.1.4 Scenario Description

The penetration level of distributed generation (DG) on the distribution feeder is measured against total load demand or the percentage of DG power referred to the rated load of the feeder. The impact of penetration level is observed by installing the DGs at two different weak nodes of the network. Node 890 and 852 are identified as weakest points of the network where the system voltage is low. Node 890 has the lowest per unit (p.u.) voltage because it is the heavily loaded node and high voltage drop in that low voltage branch due to high current. Threee different scenarios are performed. The impact is analysed by varying the penetration ratio as 10% and 20%.

(a) Scenario 1: DG at node 890

The installation of DG at the lowest voltage location:

1a) DG Size: 10% of total feeder load

1b) DG Size: 20% DG of total feeder load

The lowest voltage location is determined by running the power flow. Node 890 experiences the lowest voltage. So Node 890 is chosen for DG installation. Therefore, the sizes of DG to be installed at this location are: 176.9kW (10%) and 353.8kW (20%).

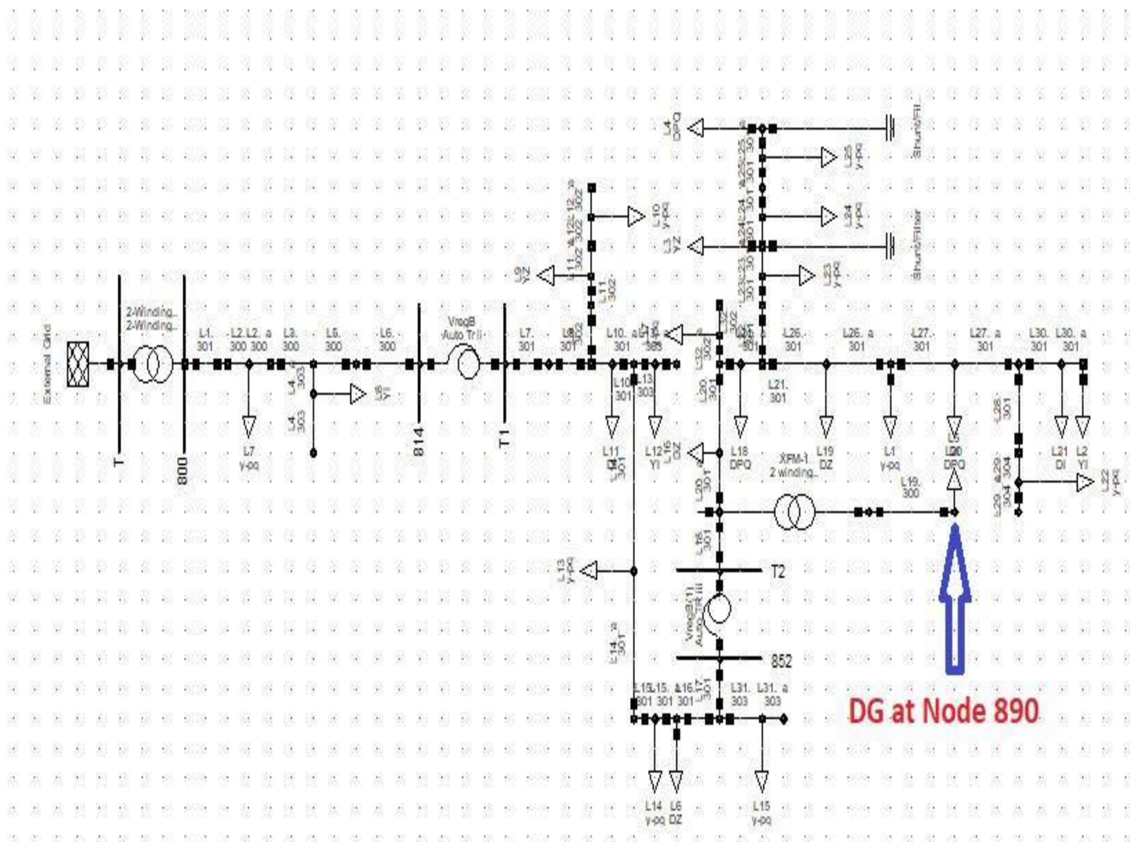


Fig 4.3 DG at lowest voltage location node 890

(b) Scenario 2: DG at node 852

Similarly, DG is also installed at another weak node 852:

2a) DG Size: 10% DG of total feeder load

2b) DG Size: 20% DG of total feeder load

The sizes of DG to be installed at this location are: 176.9kW (10%) and 353.8kW (20%)

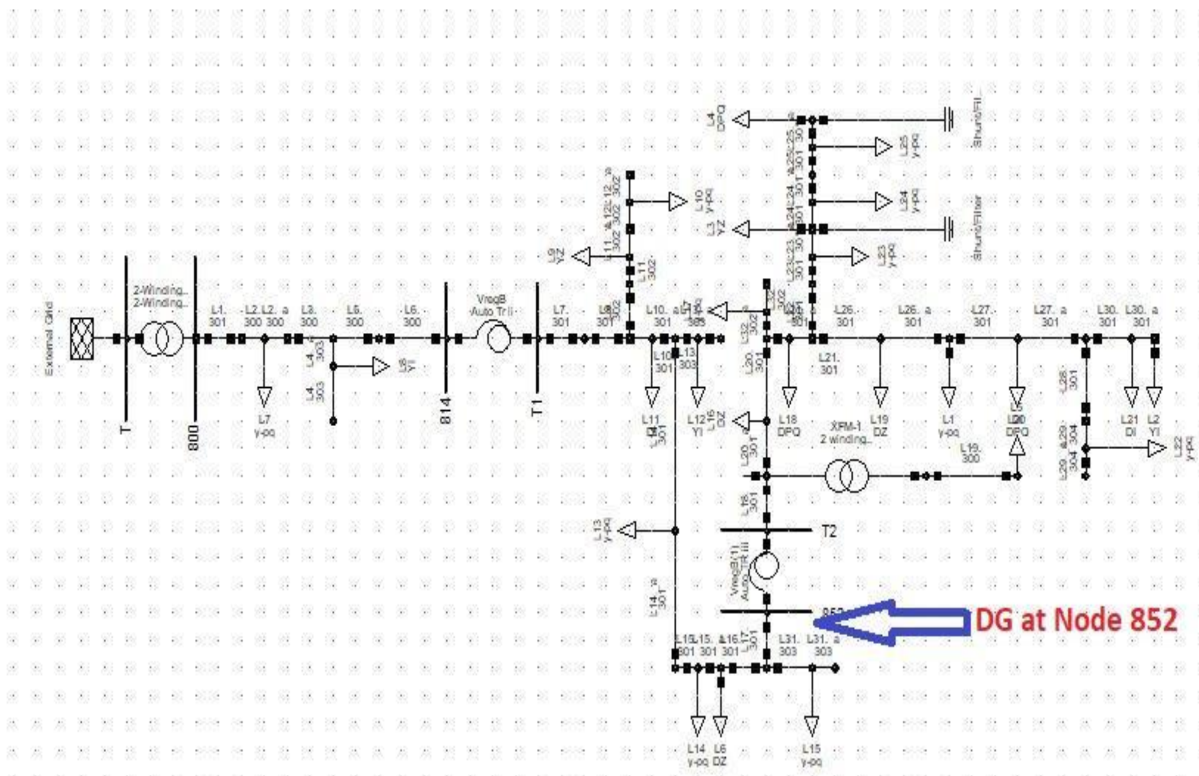


Fig 4.4 DG at node 852

(c) Scenario 3: Impact of sitting

Impact of sitting is analysed by placing DGs individually one by one at other junction nodes 808, 816, 854, 832, 834 and 840 (where laterals are branching out) assuming constant 20% penetration.

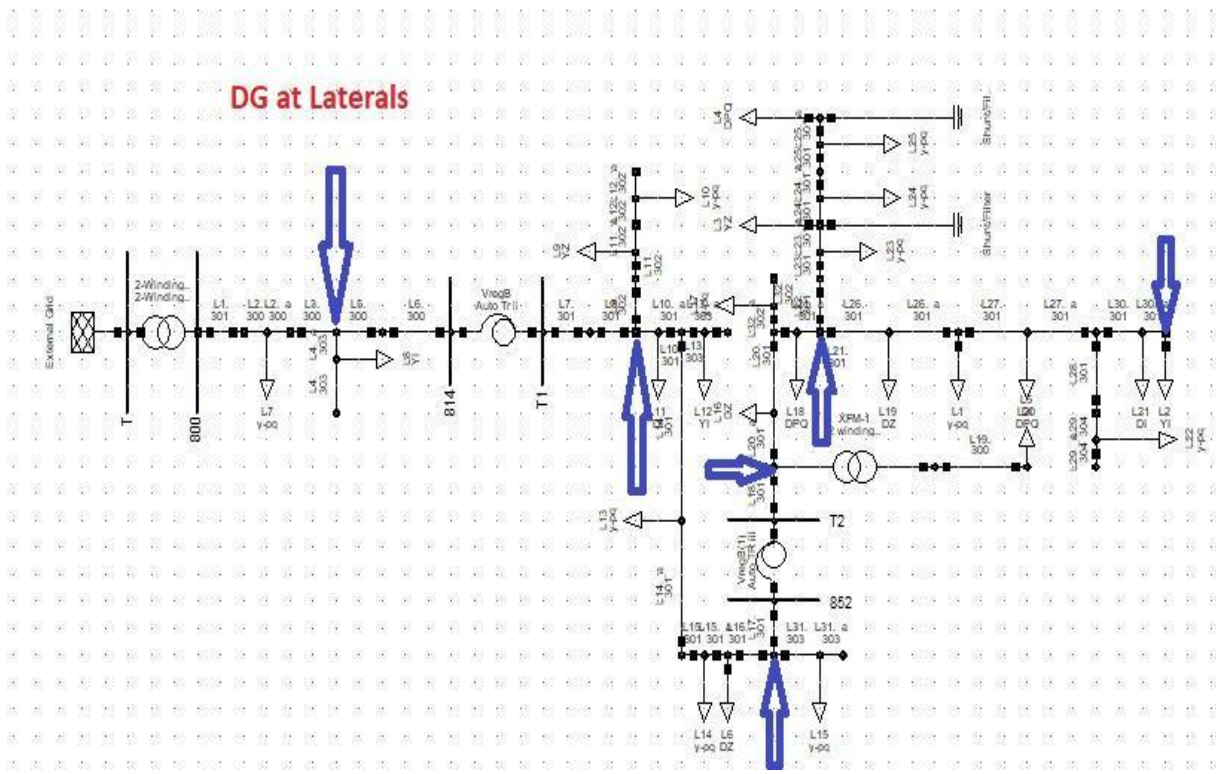


Fig 4.5 DG at Laterals, IEEE 34 Node

4.1.5 Voltage Analysis

(a) Scenario 1: DG at node 890

The end of lateral 832-890 is the only one in the network supplied by a 24.9/4.16 kV transformer, the base case profile in figure 4.6 is indicative of a heavily loaded load centre and the sloping profile is typical. Node 890 has the lowest per unit (p.u.) voltage because it is the heavily loaded node and high voltage drop in that low voltage branch due to high current. The voltage profile without DG penetration (Fig. 4.6) indicates that it is decreasing over the network length. As DG injects real power at the point of DG installation, the distribution System voltage improves as the size of DG increases as shown in the Figure 4.6 but the voltage of Node 800, 802, and 806 was equal to 1.05 p.u. in both case. The current required to serve the spot load caused enough of a voltage drop across the line between 888 and 890 to create under voltage at 890. The addition of DG at node 890 to address this under voltage reduced the branch current flowing in the lateral and the branch current in the vicinity of three nodes closest to the substation decreased thereby creating voltage equal to 1.05 p.u. for those three nodes.

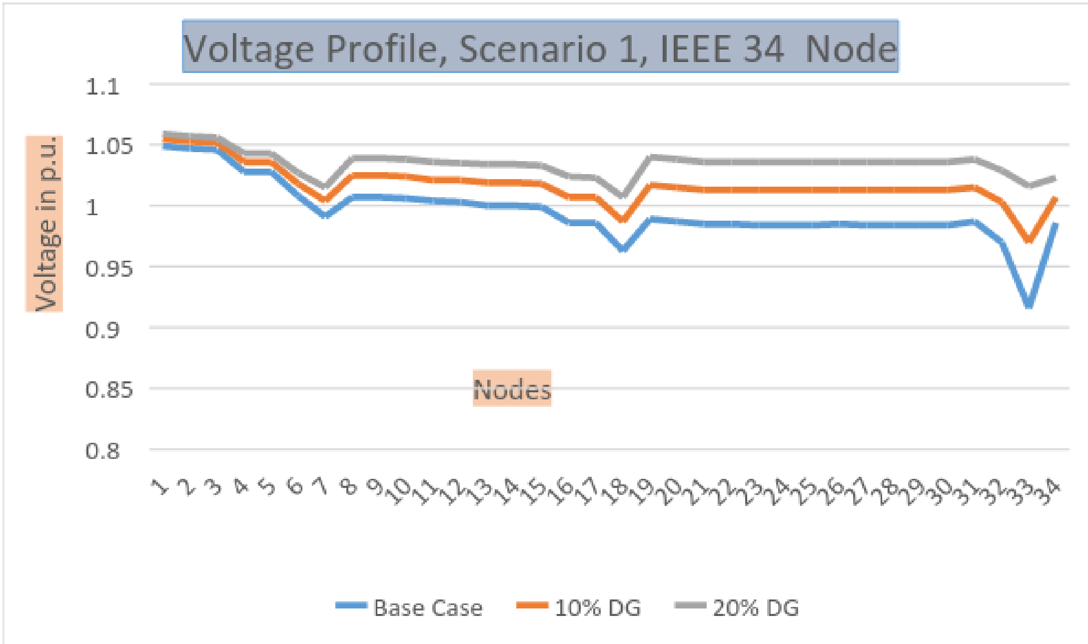


Fig 4.6 Voltage Profile, DG at node 890

(b) Scenario 2: DG at node 852

This is the second weakest node in the circuit. As DG injects real power at node 852, we can see that voltage Profile goes on improving as penetration level increases. This is because as penetration level increases in this node, there is reduction in reactive power loss as active power flows through the network due to which voltage profile gets improved.

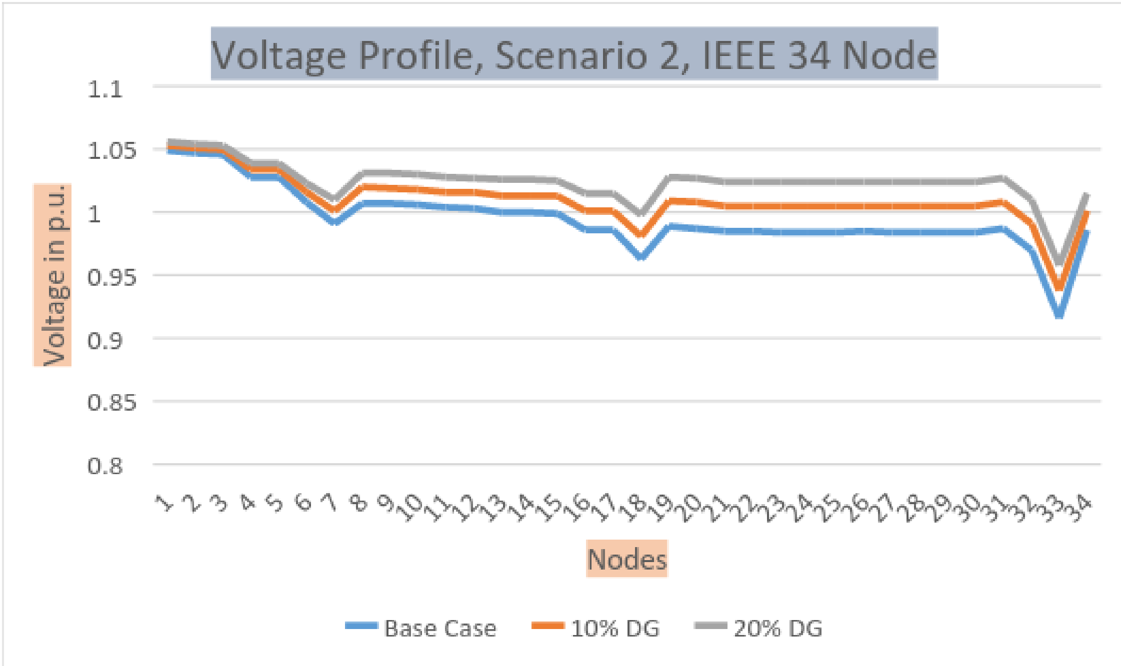


Fig 4.7 Voltage Profile, DG at node 852

Comparison between Scenario 1 (Node 890) and Scenario 2 (Node 852):

Placing a DG at node 852 produced voltages more than 1.05 pu at the same three nodes, but did not correct the under voltage at node 890 in case of 10% DG. However when 20% DG is placed, the voltage at node 890 just reached to 0.95 p.u. In between Scenario 1 and Scenario 2, we can see that voltage profile is better in scenario 1, when DG is injected at low voltage node i.e. node 890. Thus we can say that voltage profile is better when DJ is injected at low voltage location rather than any other location.

(c) Scenario 3: Impact of sitting

Impact of sitting is analysed by injecting DGs individually at other junction nodes 808, 816, 854, 832, 834 and 840 (where laterals are branching out) assuming constant 20% penetration. It is seen that voltage profile is improving as distance of DG penetration increases towards the end. This is because initially voltage was decreasing over the network length. As DG injects real power at different locations towards the end, the distribution System voltage goes on improving as shown in the figure 4.8.

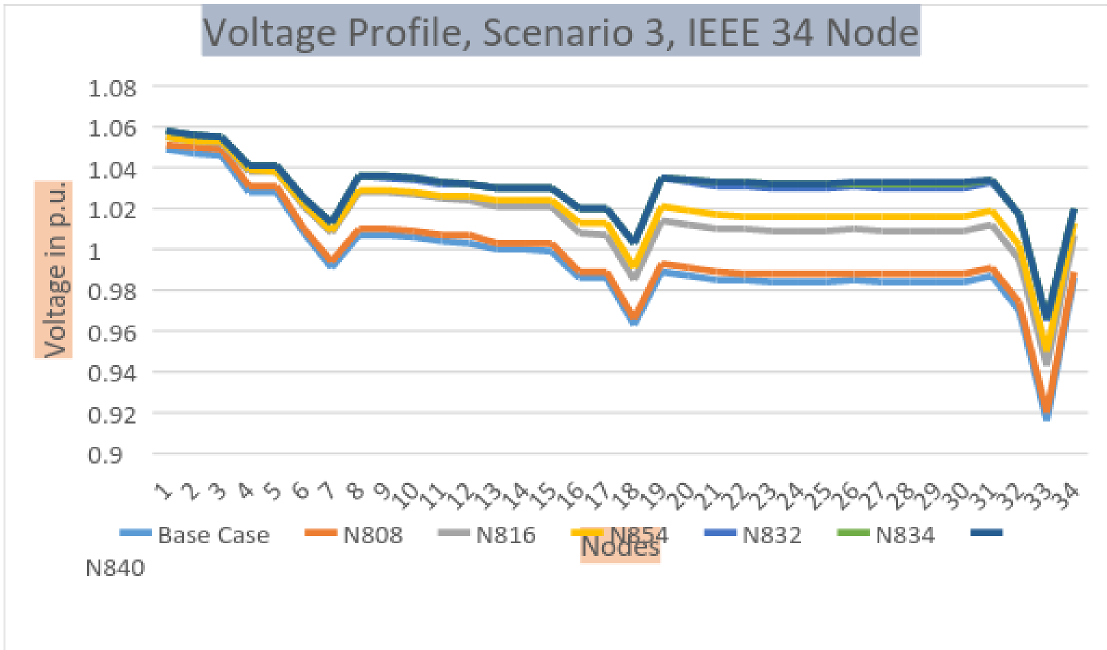


Fig 4.8 Voltage Profile, Impact of sitting, IEEE 34 Node

(d) Summary:

The summary of lowest node voltage (890) in each case after DG penetration as Table 4.2:

Table 4.2 Voltage at node 890 after installing DG

Case#	Power Injected (kW)	Voltage at Node 890 (p.u.)
Base	None	0.916
1a	10% DG at node 890	0.970
1b	20% DG at node 890	1.016
2a	10% DG at node 852	0.938
2b	20% DG at node 852	0.958
3a	20% DG at node 808	0.920
3b	20% DG at node 816	0.943
3c	20% DG at node 854	0.950
3d	20% DG at node 832	0.965

3e	20% DG at node 834	0.966
3f	20% DG at node 840	0.966

Thus, rating and location of DG unit affects the node voltage. Larger DG size increases the source of active power which improves the voltage profile throughout the distribution network. It is observed that a more uniform voltage profile along the distribution feeder is achievable if the DG is supplying a large percentage of the required demand. Voltage Profile is better when DG is installed towards the end of the line for the nodes where laterals are branching out. Voltage profile is best when installed at lowest voltage location. However, there is limit on the size of DG that can be injected depending upon the network so that the over voltage doesn't occur. However there is a possibility of voltage rise if the DG penetration level is too high (K Balamurugan, 2012).

4.1.6 System Loss Analysis

(a) Scenario 1: DG at node 890

The line losses in the distribution system are due to resistance of the overhead lines and underground cables. As the DG capacity increases, the power that flows from the grid to the distribution network reduces to meet the demand and hence the total losses decreases. In this scenario, the DG injects real power at the lowest voltage location at the node 890 and the system loss decreases because power flow reduces from the grid as DG serves the part of the load and hence loss decreases.

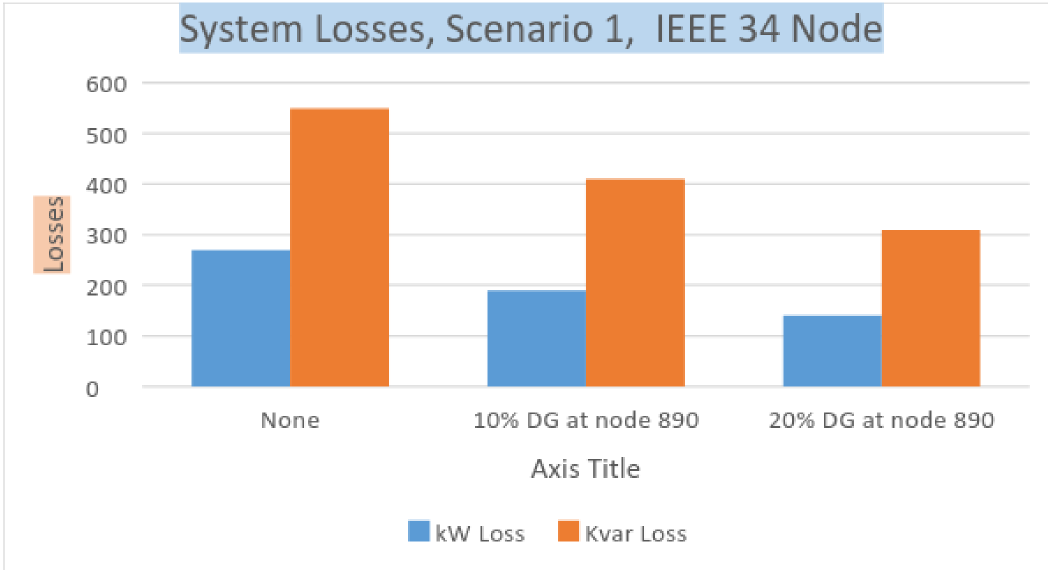


Fig 4.9 System Losses, Scenario 1(DG at node 890), IEEE 34 Node

(b) Scenario 2: DG at node 852

In this scenario, the DG injects real power at the node 852 and the system loss decreases but the loss reduction is less than that of Scenario 1.

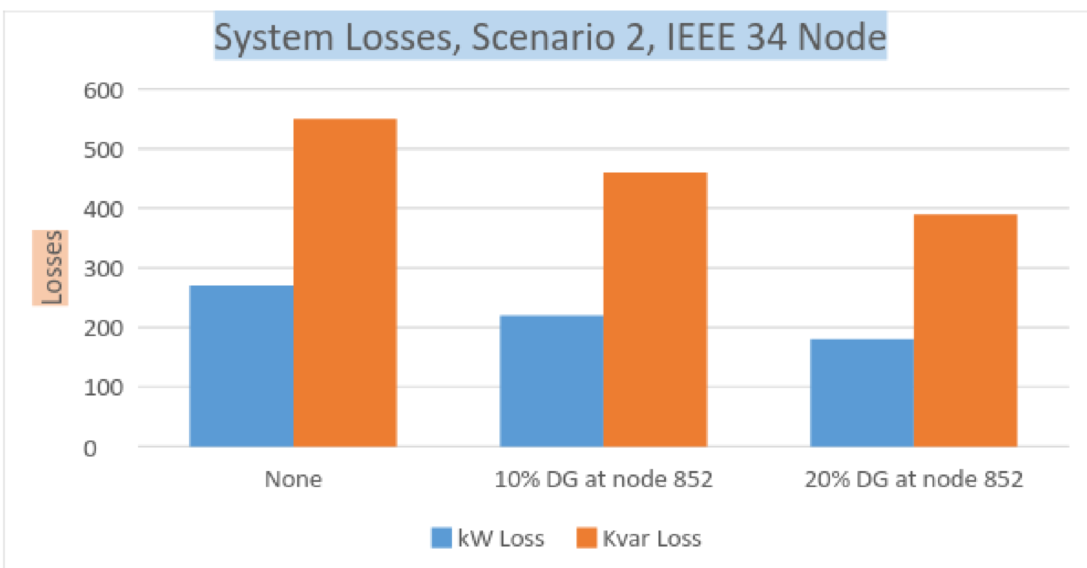


Fig 4.10: System Losses, Scenario 29(DG at node 852), IEEE 34 Node

Comparison between Scenario 1 (Node 890) and Scenario 2 (Node 852)

This decrease in power loss by adding DG makes sense, since for the base case any current supply to loads that are far away from the substation must come from the substation and hence pass through many line segments, whereas a DG closer to the downstream loads allow for a shorter current path and thus lower loss. From the results of scenario 1 and 2, we can conclude that the loss is minimum when DG is placed at the lowest voltage location.

(c) Scenario 3: Impact of sitting

Impact of sitting is analyzed by injecting DGs individually at other junction nodes 808, 816, 854, 832, 834 and 840 (where laterals are branching out) assuming constant 20% penetration. It is seen that losses reduces significantly when DG is placed towards the end of the feeder. This is because the voltage towards the end goes on decreasing before installing DG. When DG is integrated, it helps to improve the voltage profile and serves the nearby load due to which the power flow from the grid to the distribution network reduces to meet the demand and hence the total losses goes on decreasing as the location of DG is penetrated towards the end.

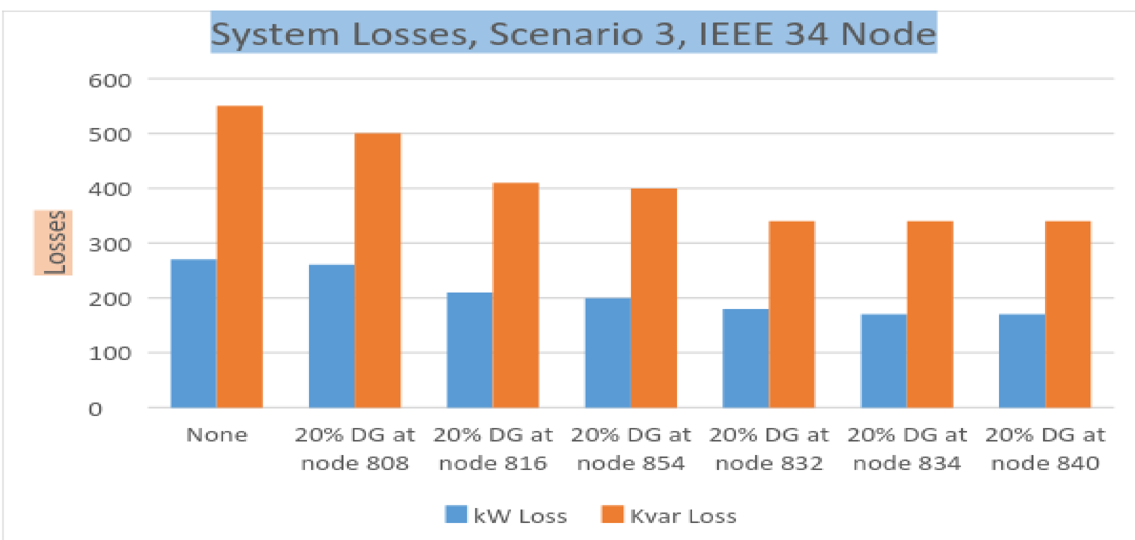


Fig 4.11: System Losses, Scenario 3(DG at Laterals node), IEEE 34 Nodes

(d) Summary

The system loss for each cases are summarized as Table 4.3:

Table 4.3 System Loss comparison, IEEE 34 Node

Case#	Power Injected (KW)	Losses	
		Kw	Kvar
Base	None	270	550
1a	10% DG at node 890	190	410
1b	20% DG at node 890	140	310
2a	10% DG at node 852	220	460
2b	20% DG at node 852	180	390
3a	20% DG at node 808	260	500
3b	20% DG at node 816	210	410
3c	20% DG at node 854	200	400
3d	20% DG at node 832	180	340
3e	20% DG at node 834	170	340
3f	20% DG at node 840	170	340

All the DG locations has decreased the power losses in the circuit compared to no DG scenario. This is due to the whole power supply to the loads from substation (bus 800) need to flow through many branches whereas in case of DGs closer to the loads scenario, most of the power is supplied by DGs. Thus, it can be seen that the loss is minimum when DG is placed at the lowest voltage location. Thus, Proper placement and size of DG units can have significant impact on system loss reduction.

4.2 Nagarkot Feeder analysis

4.2.1 Circuit Description

Nagarkot feeder is the longest feeder of Bhaktapur distribution system. Its total length is around 40 km. The circuit comprises 94 transformers with total capacity of around 8608 KVA. The peak load of the feeder is 4.26 MW which is in the month of

December/January. This network comprises mainly residential customers and few industrial customers as well. This system is modelled in DIgSILENT PowerFactory as shown in figure 4.12.

4.2.2 One line diagram

The one-line diagram of the 11 KV Nagarkot feeder is shown in figure 4.12. It is modelled in DIgSILENT PowerFactory. The diagram shows the main 3-phase 11KV line and the distribution laterals.

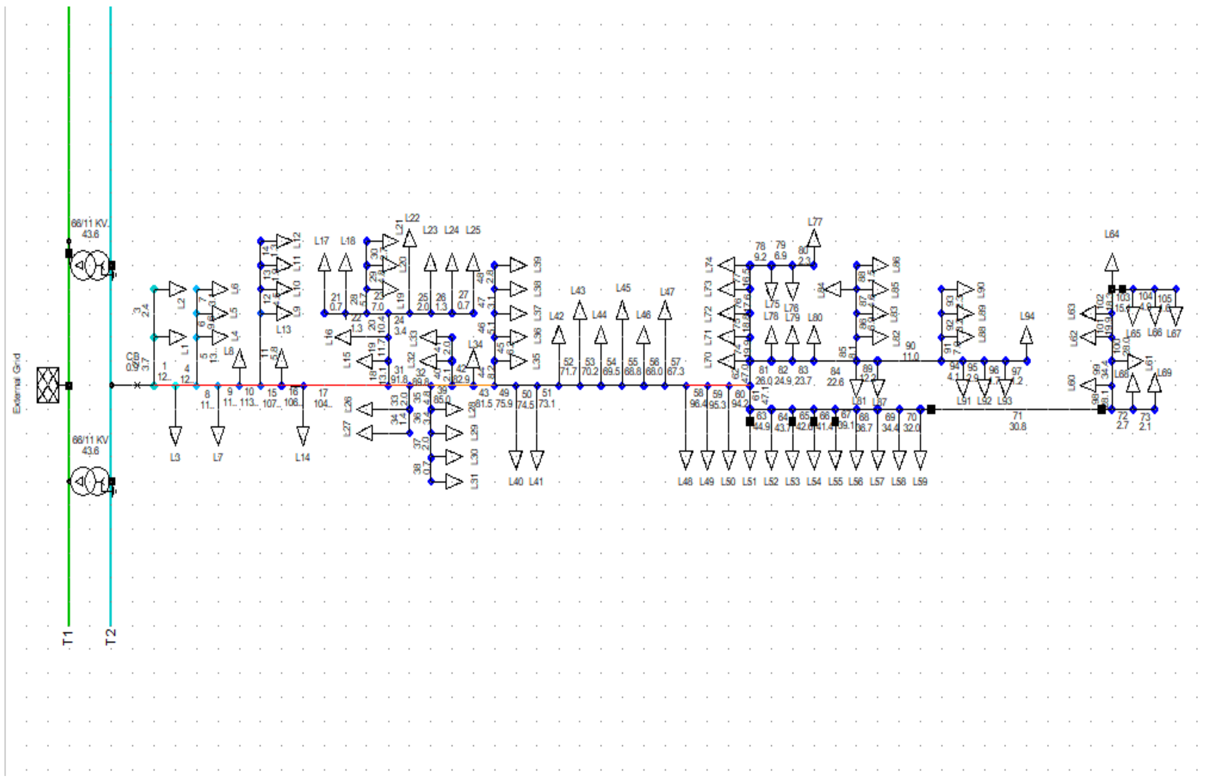


Fig 4.12 Single Line Diagram, Nagarkot feeder.

4.2.3 Scenario Description

Fourteen case studies have been conducted, which can be classified into three scenarios to illustrate the impact of size and distributed nature of DG to be installed. Scenarios 1 and 2 illustrate the impact of various DG sizes while Scenario 3 illustrates the impact of Distributing the DG at several locations on the voltage profile and losses of the system.

(a) Scenario 1

The installation of a small-scale DG of various sizes at the lowest voltage location on the main feeder:

1a) DG size: 10% of the distribution transformer load

1b) DG size: 20% of the distribution transformer load

1c) DG size: 50% of the distribution transformer load

1d) DG size: 100% of the distribution transformer load

The lowest voltage location is determined by running the power flow. At the lowest voltage location as shown in figure 4.13 in the distribution circuit of interest, the size of the distribution transformer is 100 kVA. The load of this transformer is 40kW. Therefore, the sizes of DG to be installed at this location are: 4kW (10%), 8kW (20%), 20kW (50%) and 40kW (100%).

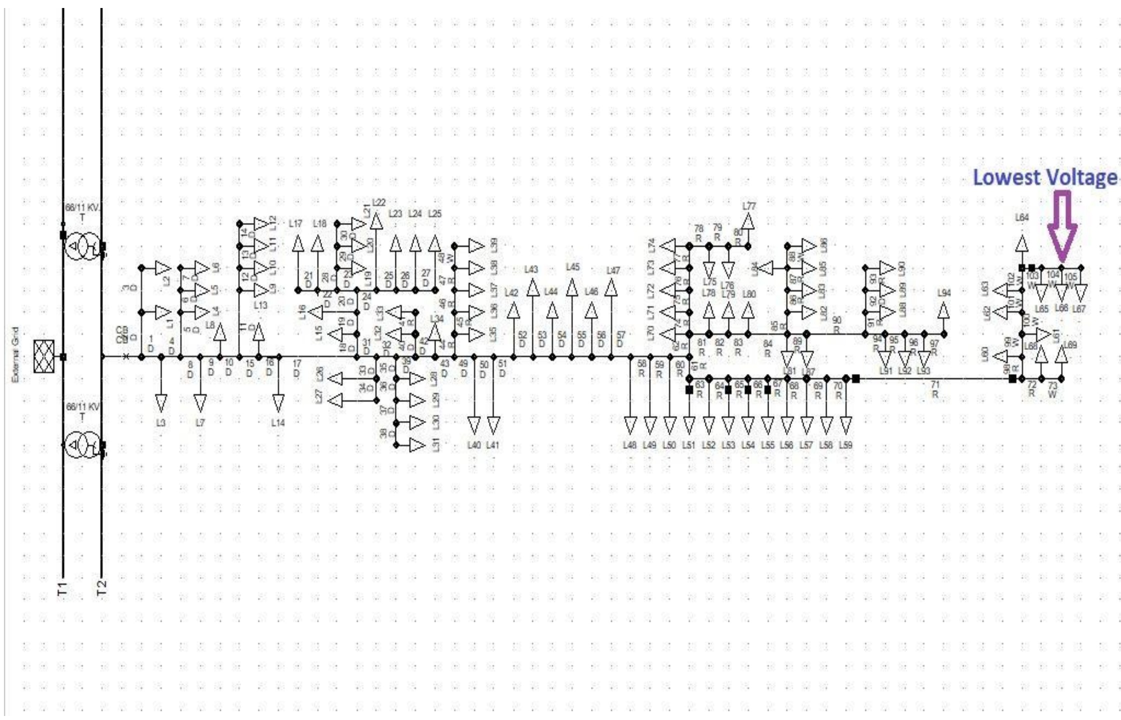


Fig 4.13 Lowest voltage location, Nagarkot feeder.

(b) Scenario 2

The installation of a large-scale DG of various sizes at the lowest voltage location on the main feeder:

2a) DG size: 10% of the total feeder load

2b) DG size: 20% of the total feeder load

2c) DG size: 50% of the total feeder load

2d) DG size: 60% of the total feeder load

2e) DG size: 70% of the total feeder load

2f) DG size: 100% of the total feeder load

Here, total load of the feeder is 4260 kW. Therefore, in this scenario, the DG size would be 426kW (10%), 852kW (20%), 2130kW (50%), 2556kW (60%), 2982kW (70%), and 4260kW (100%).

(c) Scenario 3

Distributing DGs of the same size at across 5 and 10 locations of equal length on the distribution feeder:

3a) 5 DGs: each of size 426kW (50% of total feeder load)

3b) 5 DGs: each of size 852kW (100% of total feeder load)

3c) 10 DGs: each of size 213kW (50% of total feeder load)

3d) 10 DGs: each of size 426kW (100% of total feeder load)

In this scenario, two DG sizes (50% and 100% of the total feeder load) are distributed across 5 and 10 locations of equal length as shown in figure 4.14 and 4.15 to study the impact of Distributed DG at several locations on the voltage and losses of the system.

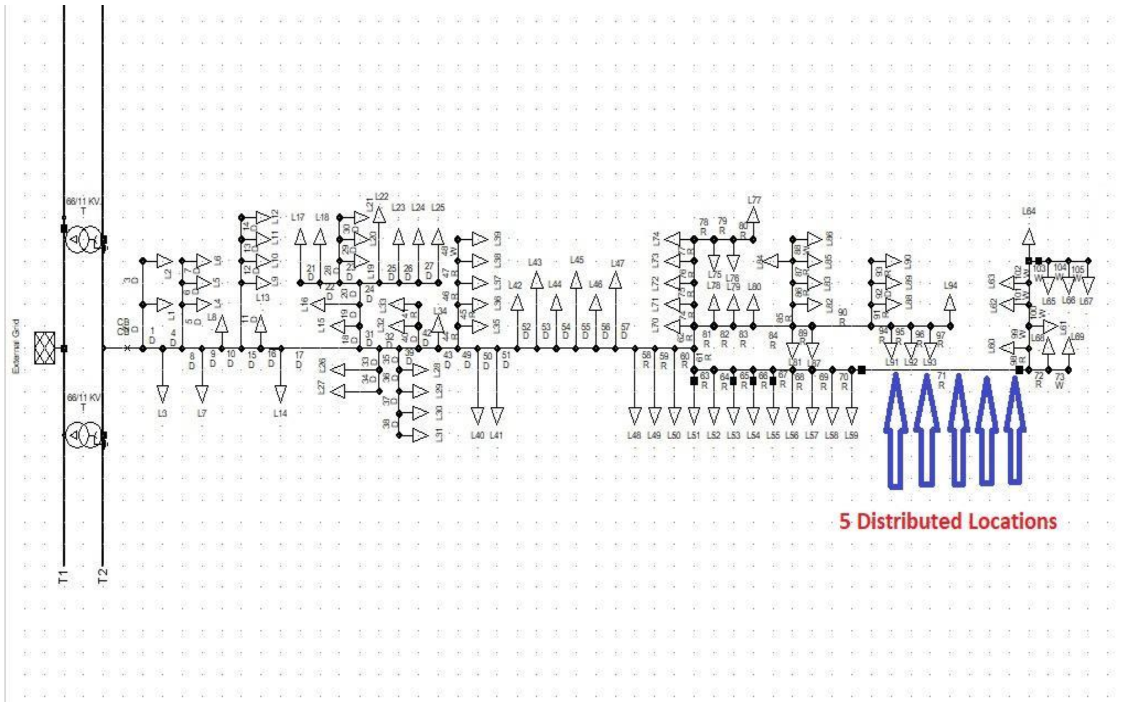


Fig 4.14 Five Distributed Locations, Nagarkot feeder.

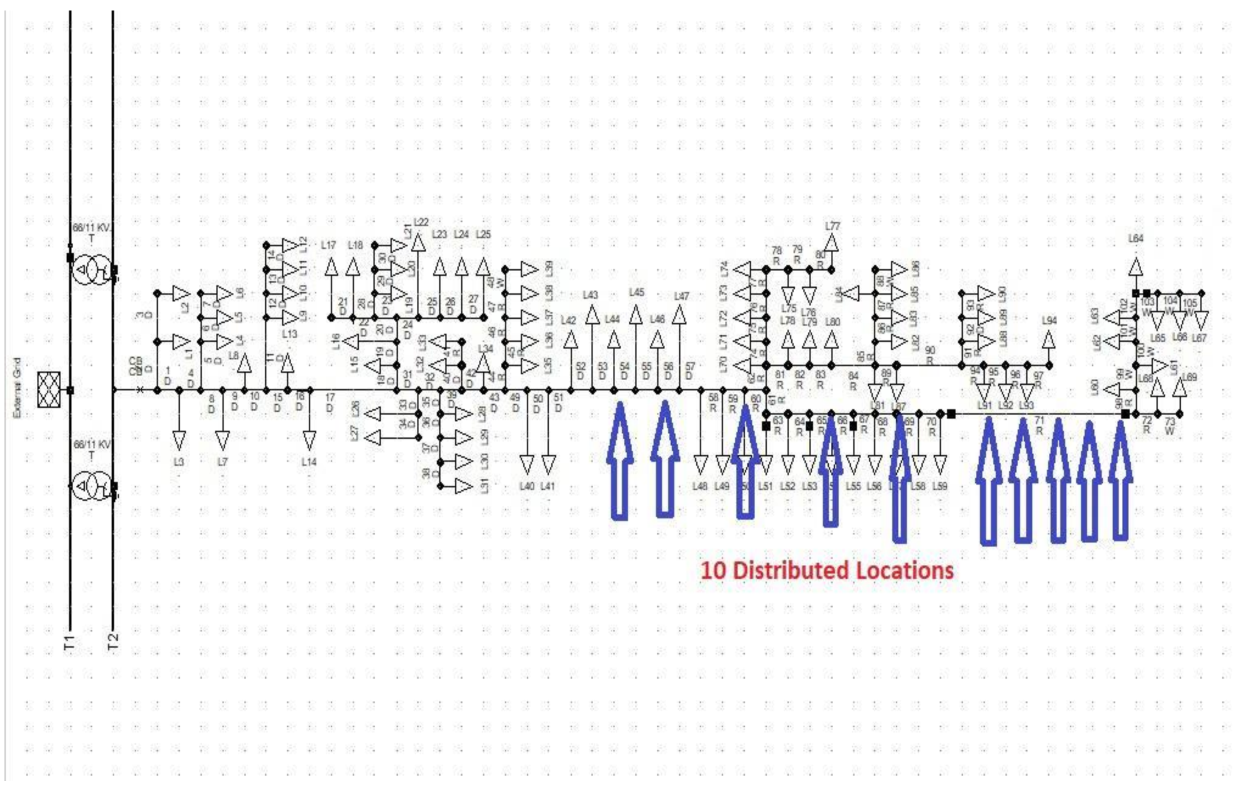


Fig 4.15 Ten Distributed Locations, Nagarkot feeder.

4.2.4 Voltage Analysis

(a) Scenario 1: Small-scale DGs

It is found that the voltage drops linearly starting from the distribution substation to the far-end load in the distribution feeder under study. As a small-scale DG injects real power at the point of DG installation, the distribution System voltage improves slightly. In this scenario, since the size of the DG is very small, the voltage impact is insignificant as shown in the figure 4.16. Installing a 100% DG (40 kW) causes slight increase in voltage (less than 1%) from the base case (NO DG).

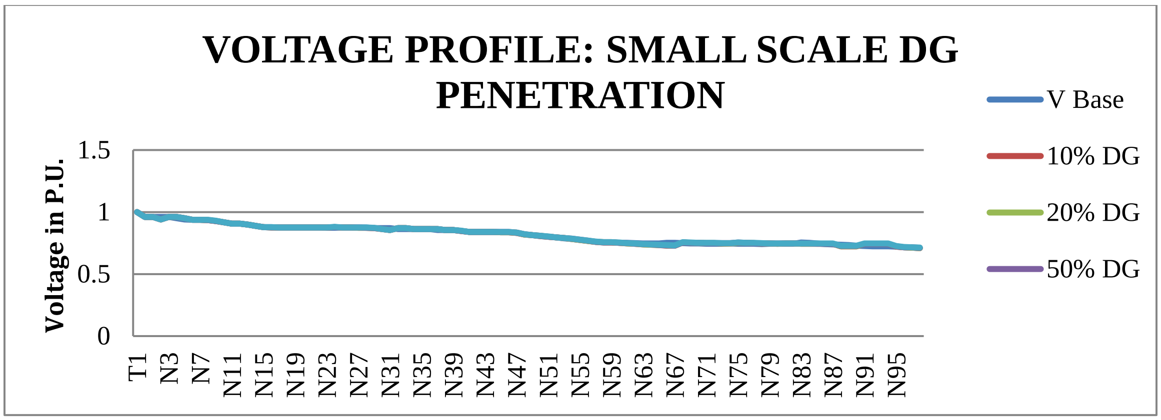


Fig 4.16 Voltage Profile comparison, Scenario 1(small scale DG), Nagarkot feeder.

(b) Scenario 2: Large-scale DG

Figure 4.19 shows that the voltage drops linearly starting from the substation to the far end load in the distribution network. As a large-scale DG injects real power at the point of DG installation, the distribution System voltage improves. The size of the DG is ranged from 426 kW to 4260 kW. However, the voltage level at all the buses is higher compared to no DG connection into the system. Simulation result proves that the connected DG shares the responsibility of supplying the required demand with the substation. It is observed that a larger capacity of DG contributes to a larger part of required demand therefore increasing the voltage level in each bus compared to the scenario without DG connection.

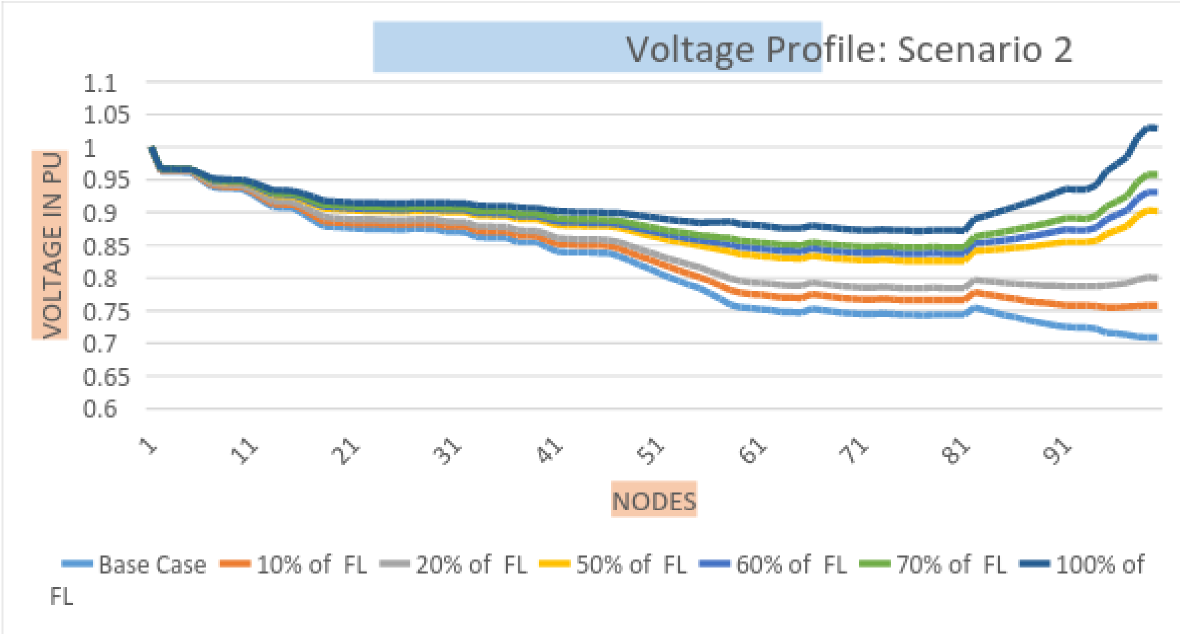


Fig 4.17 Voltage Profile comparison, Scenario 2(Large scale DG), Nagarkot feeder.

Result Comparison: Scenarios 1 & 2 (Size Impact)

In scenario 1, the voltage impact is insignificant whereas in Scenario 2, as the penetration level of DG installed on the system is increased, the overall voltage profile is maintained. When the DG is added in terms of total system load, the overall voltage is increased as shown in the figure 4.17. The voltage of node where DG is placed is increased up to approximately 20%.

(c) Scenario 3: Distributed Location Impact

In this scenario, DGs of size 50% and 100% of the total feeder load (2130kW-4260kW) are distributed across 5 and 10 locations. Distributing the DG from an aggregated location (lowest voltage) to 5 and 10 locations of equal lengths can make a positive difference to the voltage profile depending on the location and concentration of the loads. We can see from above graph that distributing 5 DGs of total feeder load each of 852 kW gives the better Voltage Profile at the end of the feeder whereas at the start of the feeder the voltage profile is almost same in case of 5 DG and 10 DG of 100% feeder load.

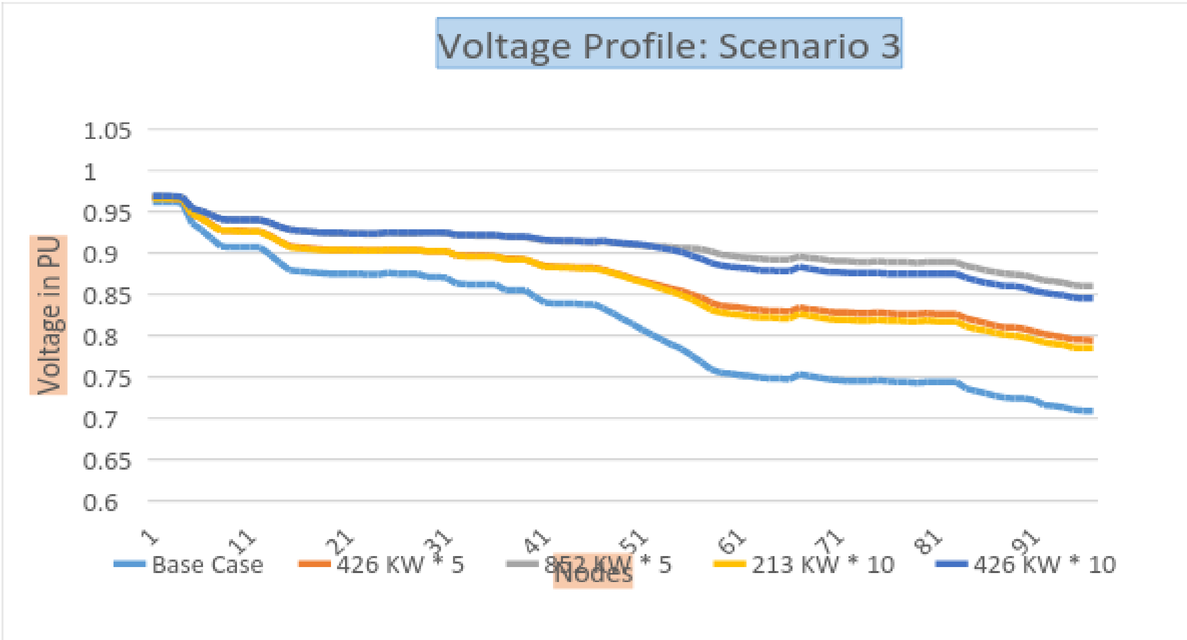


Fig 4.18 Voltage Profile comparison, Scenario 3(DG of same size at various locations), Nagarkot feeder.

(d) Summary

Thus, DG output power supplying for a larger part of required demand is able to improve the overall voltage profile along the distribution feeder. It is observed that higher voltage level of the far-end load side of the distribution network is achievable when the DG capability is increased. The results shows that a more improved voltage profile along the feeder is achievable if the DG is capable of providing a larger percentage of the required demand in the distribution network. It is obvious that the voltage level at bus increases when DG is connected. DG's function of providing part of the required demand in the distribution network improves the voltage at the point of DG connection. The lowest voltages on each case are summarized in the Table 4.4.

Table 4.4 Lowest Voltage after Installing DG, Nagarkot feeder

Case#	Power Injected	Voltage (p.u.)
Base	None	0.709
1a	4 Kw	0.710
1b	8 Kw	0.710

1c	20 Kw	0.712
1d	40 kW	0.714
2a	426 Kw	0.758
2b	852 kW	0.800
2c	2130 kW	0.902
2d	2556 kW	0.931
2e	2982 kW	0.958
2f	4260 kW	1.029
3a	426 kW * 5 locations	0.794
3b	852 kW * 5 locations	0.860
3c	213 kW * 10 locations	0.785
3d	426 kW * 10 locations	0.845

4.2.5 System Loss Analysis

(a) Scenario 1: Small-scale DG

In this scenario, the small-scale DG (4kW-20kW) injects real power at the lowest voltage Locations and the system losses decrease. Due to the small size of DG, the impact is small as shown in figure 4.19. As shown in the figure, the system losses decrease from 1040 kW to 1020 kW(approx. 2%) and from 1280 Mvar to 1260 Mvar (approx. 1.5%) as we install a DG of size 100% of distribution transformer load (40kW) at the lowest voltage location.

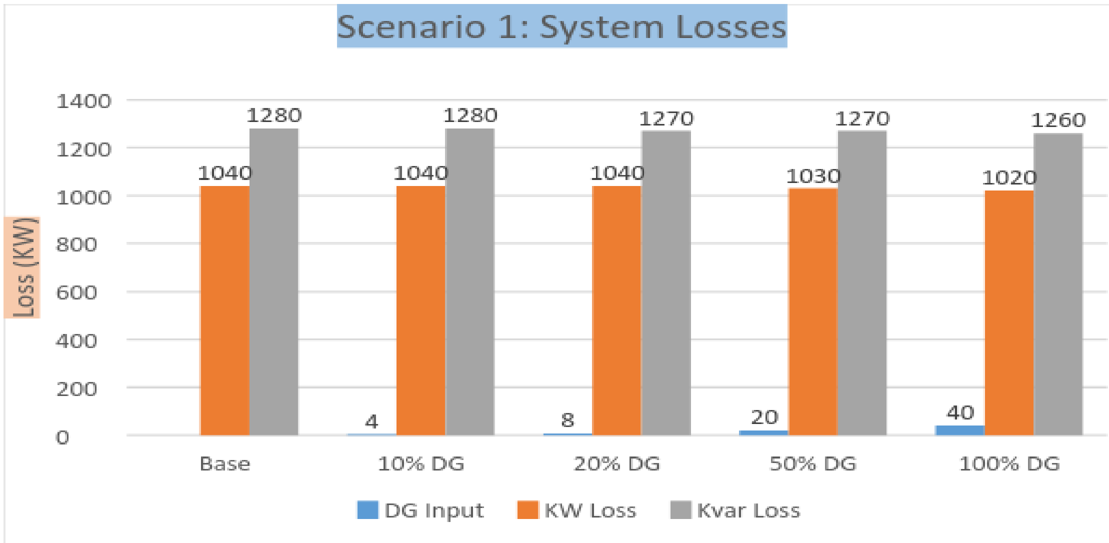


Fig 4.19 System Losses, Scenario 1(small scale DG), Nagarkot feeder

(b) Scenario 2: Large-scale DG

In this scenario, the large scale DG (426kW-4260kW) injects real power at the lowest voltage location and the systems losses reduce significantly. The results for different load penetrations are graphically shown in the figure 4.20 below.

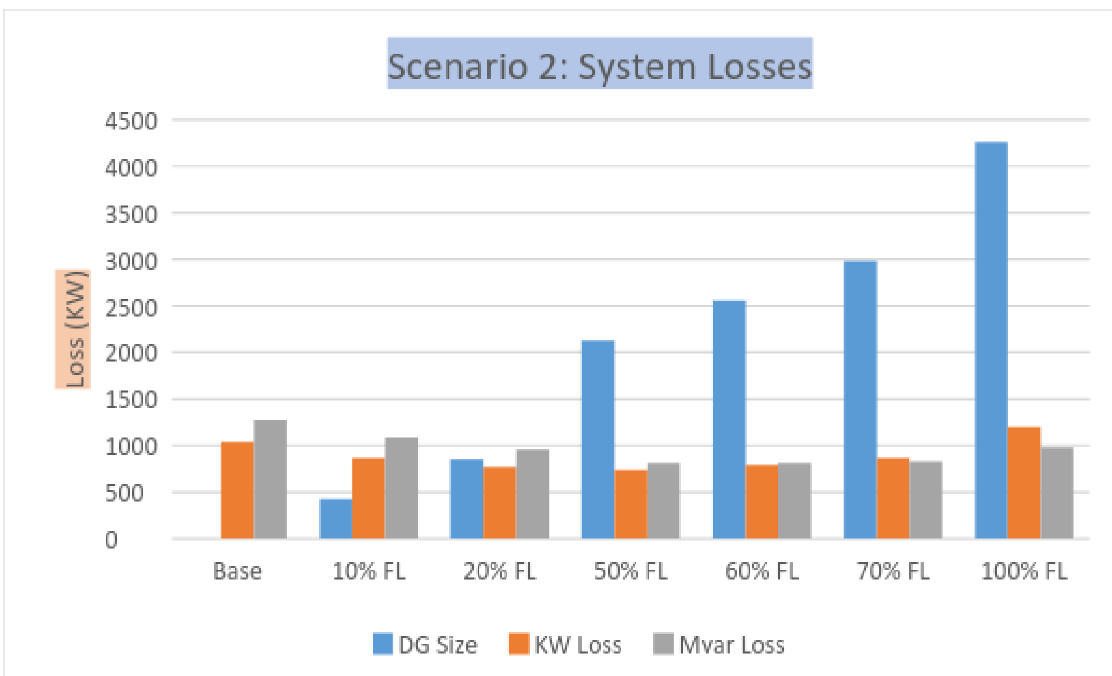


Fig 4.20 System Losses, Scenario 2(Large scale DG), Nagarkot feeder

As shown in the figure above, when size of DG is 50% of total feeder load (2130 kW), the systems losses reduce significantly from 1040 kW to 740 kW (28.8%) and from 1280 MVAR to 810 MVAR (36.71%). It has been found that installing a 50% DG i.e. (2130kW) causes more reduction of losses than adding 100% DG i.e. (4260kW). This shows that the total losses vary when the DG output changes as shown in figure 4.20. The losses will be minimum when the distance of all the load points to source is minimum. So, the losses decrease when DG is injected in a distribution network at a suitable location because the power flow from the grid to the distribution network reduces to meet the demand and DG serves that particular load. When the size of DG increases further the losses reduce further up to a saturation point after which DG current increases if the size of DG is increased which travel longer distance to meet the more demand. Loss increases as current travels longer distance to serve the load.

It can be seen that loss increases as the size of DG increases beyond 50%. This is because DG current increases further which travel longer distance to meet the demand and also the thermal limit of the line is exceeded. Loss increases after certain level of DG current as current travels longer distance to serve the load (Rao, Obulesh, 2013).

(c) Scenario 3: Distributed Location Impact

In this scenario, the large-scale DG is distributed to 5 and 10 locations of equal length to study the impacts of distributing DG to several locations. Distributing the aggregated DG to 5 and 10 locations can reduces the losses as shown in figure 4.23 below.

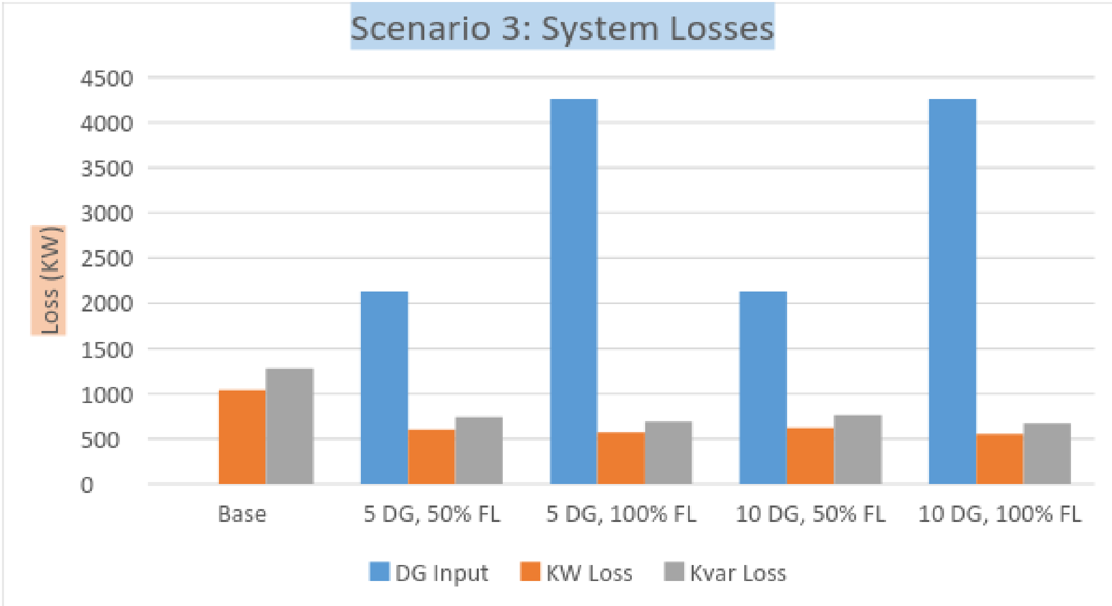


Fig 4.21 System Losses, Scenario 3(DG of same size at various locations), Nagarkot feeder

It is observed from the figure above that distributing the 100% DG (4260 kW) at 10 locations can reduce the losses significantly instead of installing an aggregated DG at one location. In this case, the losses reduce from 1040 kW to 550 kW (47%) and from 1280 Mvar to 670 Mvar (47%). This result is expected because in this case multiple DG serves multiple loads at the point of installation. The distance between the source and the load is minimum in this case. Hence, there is huge reduction of losses in this case.

(d) Summary

The system losses for each cases are shown in the Table 4.6 .

Table 4.5 System Loss comparison, Nagarkot feeder

		Losses	
Case#	**Power Injected**	**kW**	**Kvar**
Base	None	1040	1280
1a	4 kW	1040	1280
1b	8 kW	1040	1270
1c	20 kW	1030	1270

1d	40 kW	1020	1260
2a	426 kW	870	1090
2b	852 kW	770	960
2c	2130 kW	740	810
2d	2556 kW	790	810
2e	2982 kW	870	830
2f	4260 kW	1200	980
3a	426 kW * 5 locations	600	740
3b	852 kW * 5 locations	570	690
3c	213 kW * 10 locations	620	760
3d	426 kW * 10 locations	550	670

Thus, it can be seen that distributing the 100% DG (4260 kW) at 10 locations can reduce the losses significantly instead of installing an aggregated DG at one location. This is due to the fact that DG serves the load nearby with minimum current path due to which the loss reduces significantly. From above results we can conclude that there are various impacts of DG of different sizes and at different locations.

CHAPTER FIVE: CONCLUSIONS AND RECOMMENDATION

5.1 Conclusions

Conclusions from the case studies are:

- Injection of any size of DG improves the voltage profile and decreases the losses than no DG case.
- Voltage profile is better when large scale DG is injected at the lowest voltage location rather than any other location.
- Loss is minimum when large scale DG is injected at the lowest voltage location
- The obtained results indicate that the DG influences the distribution network and that their precise location and size are vital in reducing power losses and improving the voltage Profile.
- Distributing the DG at 5 or 10 locations can have positive impacts on the voltage depending on the concentration of loads.

5.2 Recommendation

Further analysis can be performed by installing different types of DGs that inject both real & reactive power into the distribution network. The behavior of different types of DG on a distribution network can be investigated. For example, PV and wind turbines output fluctuates significantly as the sun and wind intensity change respectively and these impacts can be considered in the analysis. Distributed generation may cause noticeable voltage flicker and introduce harmonics into the system. Further research could also focus on the impacts of DG on the short circuit levels of the system and the islanding and re-connection operation of the DG.

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APPENDIX

A. IEEE 34 Node Test Feeder Data and Simulation Results

Table A1: Line Segment Data

Node A	Node B	Length(ft.)	Config.
800	802	2580	300
802	806	1730	300
806	808	32230	300
808	810	5804	303
808	812	37500	300
812	814	29730	300
814	850	10	301
816	818	1710	302
816	824	10210	301
818	820	48150	302
820	822	13740	302
824	826	3030	303
824	828	840	301
828	830	20440	301
830	854	520	301
832	858	4900	301
832	888	0	XFM-1
834	860	2020	301
834	842	280	301
836	840	860	301
836	862	280	301
842	844	1350	301
844	846	3640	301
846	848	530	301
850	816	310	301
852	832	10	301
854	856	23330	303
854	852	36830	301
858	864	1620	302
858	834	5830	301
860	836	2680	301
862	838	4860	304
888	890	10560	300

Table A2: Overhead Line Configurations

Config.	Phasing	Phase	Neutral	Spacing ID
		ACSR	ACSR	
300	B A C N	1/0	1/0	500
301	B A C N	#2 6/1	#2 6/1	500
302	A N	#4 6/1	#4 6/1	510
303	B N	#4 6/1	#4 6/1	510
304	B N	#2 6/1	#2 6/1	510

Table A3: Transformer Data

	kVA	kV-high	kV-low	R - %	X - %
Substation:	2500	69 – D	24.9 - Gr. W	1	8
XFM -1	500	24.9 - Gr.W	4.16 - Gr. W	1.9	4.08

Table A4: Spot Loads

Node	Load	Ph-1	Ph-1	Ph-2	Ph-2	Ph-3	Ph-4
	Model	kW	kVAr	kW	kVAr	kW	kVAr
860	Y-PQ	20	16	20	16	20	16
840	Y-I	9	7	9	7	9	7
844	Y-Z	135	105	135	105	135	105
848	D-PQ	20	16	20	16	20	16
890	D-I	150	75	150	75	150	75
830	D-Z	10	5	10	5	25	10
Total		344	224	344	224	359	229

Table A5: shunt Capacitors

Node	Ph-A	Ph-B	Ph-C
	kVAr	kVAr	kVAr
844	100	100	100
848	150	150	150
Total	250	250	250

Table A6: Distributed Loads

Node A	Node B	Load Model	Ph-1 kW	Ph-1 kVAr	Ph-2 kW	Ph-2 kVAr	Ph-3 kW	Ph-3 kVAr
802	806	Y-PQ	0	0	30	15	25	14
808	810	Y-I	0	0	16	8	0	0
818	820	Y-Z	34	17	0	0	0	0
820	822	Y-PQ	135	70	0	0	0	0
816	824	D-I	0	0	5	2	0	0
824	826	Y-I	0	0	40	20	0	0
824	828	Y-PQ	0	0	0	0	4	2
828	830	Y-PQ	7	3	0	0	0	0
854	856	Y-PQ	0	0	4	2	0	0
832	858	D-Z	7	3	2	1	6	3
858	864	Y-PQ	2	1	0	0	0	0
858	834	D-PQ	4	2	15	8	13	7
834	860	D-Z	16	8	20	10	110	55
860	836	D-PQ	30	15	10	6	42	22
836	840	D-I	18	9	22	11	0	0
862	838	Y-PQ	0	0	28	14	0	0
842	844	Y-PQ	9	5	0	0	0	0
844	846	Y-PQ	0	0	25	12	20	11
846	848	Y-PQ	0	0	23	11	0	0
Total			262	133	240	120	220	114

Table A7: Regulator Data

Regulator ID:	1		
Line Segment:	814 - 850		
Location:	814		
Phases:	A - B -C		
Connection:	3-Ph,LG		
Monitoring Phase:	A-B-C		
Bandwidth:	2.0 volts		
PT Ratio:	120		
Primary CT Rating:	100		
Compensator Settings:	Ph-A	Ph-B	Ph-C
R - Setting:	2.7	2.7	2.7
X - Setting:	1.6	1.6	1.6
Volltage Level:	122	122	122
Regulator ID:	2		

Line Segment:	852 - 832		
Location:	852		
Phases:	A - B -C		
Connection:	3-Ph,LG		
Monitoring Phase:	A-B-C		
Bandwidth:	2.0 volts		
PT Ratio:	120		
Primary CT Rating:	100		
Compensator Settings:	Ph-A	Ph-B	Ph-C
R - Setting:	2.5	2.5	2.5
X - Setting:	1.5	1.5	1.5
Volltage Level:	124	124	124

Table A8: Impedances for different configurations

Configuration 300:

--------- Z & B Matrices Before Changes ---------

```
         Z (R +jX) in ohms per mile
 1.3368  1.3343   0.2101  0.5779   0.2130  0.5015
                  1.3238  1.3569   0.2066  0.4591
                                   1.3294  1.3471
        B in micro Siemens per mile
   5.3350   -1.5313   -0.9943
             5.0979   -0.6212
                       4.8880
```

Configuration 301:

```
         Z (R +jX) in ohms per mile
 1.9300  1.4115   0.2327  0.6442   0.2359  0.5691
                  1.9157  1.4281   0.2288  0.5238
                                   1.9219  1.4209
        B in micro Siemens per mile
   5.1207   -1.4364   -0.9402
             4.9055   -0.5951
                       4.7154
```

Configuration 302:

```
         Z (R +jX) in ohms per mile
 2.7995  1.4855   0.0000  0.0000   0.0000  0.0000
                  0.0000  0.0000   0.0000  0.0000
                                   0.0000  0.0000
        B in micro Siemens per mile
   4.2251    0.0000    0.0000
             0.0000    0.0000
                       0.0000
```

Table A9: IEEE Positive Sequence Voltages

Node	Positive sequence Voltages (p.u.)
800	1.05000
802	1.04810
806	1.04683
808	1.02403
810	1.02940
812	0.99773
814	0.97682
REG10	1.02115
850	1.02115
816	1.02082
818	1.01630
820	0.99260
822	0.98950
824	1.01185
826	1.01560
828	1.01112
830	0.99378
854	0.99338
852	0.96324
REG11	1.03544
832	1.03544
858	1.03317
834	1.03053
842	1.03050
844	1.03027
846	1.03040
848	1.03047
860	1.03017

836	1.02990
840	1.02990
862	1.02990
838	1.02850
864	1.03360
XF10	0.99930
888	0.99927
890	0.91924
856	0.99770

Tabel A10: IEEE average Voltage and PowerFactory Node voltage in p.u.

Nodes	IEEE Average V in p.u.	PowerFactory V in p.u.	% differences
800	1.0500	1.049	-0.09524
802	1.0481	1.047	-0.10495
806	1.0474	1.046	-0.13652
808	1.0240	1.028	0.38768
810	1.0294	1.028	-0.13600
812	0.9977	1.008	1.02933
814	0.9768	0.991	1.45061
850	1.0211	1.007	-1.38762
816	1.0208	1.007	-1.35478
818	1.0163	1.006	-1.01348
820	0.9926	1.004	1.14849
822	0.9895	1.003	1.36432
824	1.0118	1.000	-1.17308
826	1.0156	1.000	-1.53604
828	1.0111	0.999	-1.19965
830	0.9938	0.986	-0.78487
854	0.9835	0.986	0.25419

852	0.9632	0.963	-0.02803
832	1.0354	0.989	-4.48782
858	1.0332	0.987	-4.47154
834	1.0305	0.985	-4.42182
842	1.0305	0.985	-4.41811
844	1.0303	0.984	-4.50033
846	1.0304	0.984	-4.50589
848	1.0305	0.984	-4.51237
860	1.0302	0.985	-4.38750
836	1.0299	0.984	-4.45953
840	1.0299	0.984	-4.45953
862	1.0299	0.984	-4.45953
838	1.0285	0.984	-4.32669
864	1.0336	0.987	-4.50851
888	0.9993	0.970	-2.93497
890	0.9193	0.916	-0.35897
856	0.9977	0.986	-1.17270

Tabel A11: Node Voltages in p.u. after Simulation, Scenario 1

Nodes	**Base V, p.u.**	**10% DG, p.u.**	**20% DG, p.u.**
800	1.049	1.055	1.059
802	1.047	1.053	1.057
806	1.046	1.052	1.056
808	1.028	1.036	1.043
810	1.028	1.036	1.043
812	1.008	1.018	1.027
814	0.991	1.004	1.015
850	1.007	1.025	1.039
816	1.007	1.025	1.039

818	1.006	1.024	1.038
820	1.004	1.021	1.036
822	1.003	1.021	1.035
824	1.000	1.019	1.034
826	1.000	1.019	1.034
828	0.999	1.018	1.033
830	0.986	1.007	1.024
854	0.986	1.007	1.023
852	0.963	0.987	1.007
832	0.989	1.017	1.04
858	0.987	1.015	1.038
834	0.985	1.013	1.036
842	0.985	1.013	1.036
844	0.984	1.013	1.036
846	0.984	1.013	1.036
848	0.984	1.013	1.036
860	0.985	1.013	1.036
836	0.984	1.013	1.036
840	0.984	1.013	1.036
862	0.984	1.013	1.036
838	0.984	1.013	1.036
864	0.987	1.015	1.038
888	0.97	1.003	1.029
890	0.916	0.97	1.016
856	0.986	1.007	1.023

Table A12: Node Voltages in p.u. after Simulation, Scenario 2

Nodes	Base V, p.u.	10% DG, p.u.	20% DG, p.u.
800	1.049	1.053	1.056

802	1.047	1.051	1.054
806	1.046	1.050	1.053
808	1.028	1.034	1.039
810	1.028	1.034	1.039
812	1.008	1.016	1.023
814	0.991	1.001	1.010
850	1.007	1.02	1.031
816	1.007	1.019	1.031
818	1.006	1.018	1.03
820	1.004	1.016	1.028
822	1.003	1.016	1.027
824	1.000	1.013	1.026
826	1.000	1.013	1.026
828	0.999	1.013	1.025
830	0.986	1.001	1.015
854	0.986	1.001	1.015
852	0.963	0.981	0.998
832	0.989	1.009	1.028
858	0.987	1.008	1.027
834	0.985	1.005	1.024
842	0.985	1.005	1.024
844	0.984	1.005	1.024
846	0.984	1.005	1.024
848	0.984	1.005	1.024
860	0.985	1.005	1.024
836	0.984	1.005	1.024
840	0.984	1.005	1.024
862	0.984	1.005	1.024
838	0.984	1.005	1.024

864	0.987	1.008	1.027
888	0.970	0.991	1.01
890	0.916	0.938	0.958
856	0.986	1.001	1.015

Table A14: Node Voltages in p.u. after Simulation, Scenario 3

Nodes	Base V, p.u.	N808	N816	N854	N832	N834	N840
800	1.049	1.051	1.055	1.055	1.058	1.058	1.058
802	1.047	1.050	1.053	1.053	1.056	1.056	1.056
806	1.046	1.049	1.052	1.053	1.055	1.055	1.055
808	1.028	1.031	1.038	1.039	1.041	1.041	1.041
810	1.028	1.031	1.038	1.038	1.041	1.041	1.041
812	1.008	1.010	1.021	1.022	1.025	1.025	1.025
814	0.991	0.994	1.008	1.009	1.013	1.013	1.013
850	1.007	1.010	1.028	1.029	1.036	1.036	1.036
816	1.007	1.010	1.028	1.029	1.035	1.036	1.036
818	1.006	1.009	1.027	1.028	1.034	1.035	1.035
820	1.004	1.007	1.025	1.026	1.032	1.033	1.033
822	1.003	1.007	1.024	1.026	1.032	1.032	1.032
824	1.000	1.003	1.021	1.024	1.030	1.030	1.030
826	1.000	1.003	1.021	1.024	1.030	1.030	1.030
828	0.999	1.003	1.021	1.024	1.030	1.030	1.030
830	0.986	0.989	1.008	1.013	1.020	1.020	1.020
854	0.986	0.989	1.007	1.013	1.020	1.020	1.020
852	0.963	0.966	0.985	0.991	1.003	1.003	1.003
832	0.989	0.993	1.014	1.021	1.035	1.035	1.035
858	0.987	0.991	1.012	1.019	1.033	1.034	1.034
834	0.985	0.989	1.010	1.017	1.031	1.033	1.033
842	0.985	0.988	1.010	1.016	1.031	1.033	1.033

844	0.984	0.988	1.009	1.016	1.030	1.032	1.032
846	0.984	0.988	1.009	1.016	1.030	1.032	1.032
848	0.984	0.988	1.009	1.016	1.030	1.032	1.032
860	0.985	0.988	1.010	1.016	1.031	1.032	1.033
836	0.984	0.988	1.009	1.016	1.030	1.032	1.033
840	0.984	0.988	1.009	1.016	1.030	1.032	1.033
862	0.984	0.988	1.009	1.016	1.030	1.032	1.033
838	0.984	0.988	1.009	1.016	1.030	1.032	1.033
864	0.987	0.991	1.012	1.019	1.033	1.034	1.034
888	0.970	0.974	0.995	1.002	1.017	1.017	1.017
890	0.916	0.920	0.943	0.950	0.965	0.966	0.966
856	0.986	0.989	1.007	1.013	1.020	1.020	1.020

B. Nagarkot Feeder Data and Simulation Results

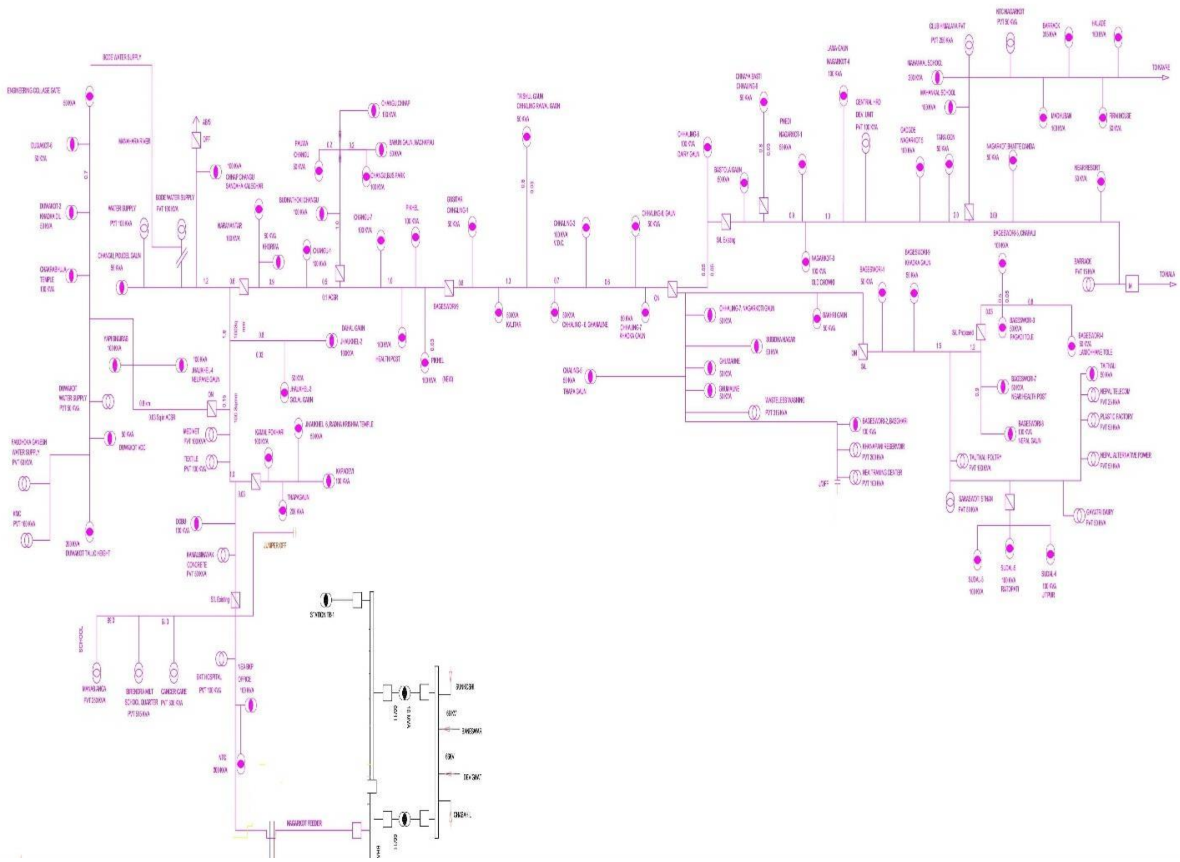

Fig B1: Single Line Diagram of 11 kV Nagarkot Feeder with Transformer details and locations

Table B1: 11 kV Line Details, Nagarkot Feeder

Overhead		
0.03 sq. Inch Conductor Length (in Km)	0.05 sq. Inch Conductor Length (in Km)	0.1 sq. Inch Conductor Length (in Km)
4.28	12.51	24.07

Table B2: Consumers Connection Numbers

Consumer Connections Number	
Single Phase	Three Phase
5924	174

Table B3: Feeder Load

Peak Load (in A)					
Shrawan	Bhadra	Ashoj	Kartik	Mangsir	Poush
180	182	220	210	245	280

Table B4: Node Voltages in p.u. after simulation, Scenario 1

Nodes	V Base	Case 1a	Case 1b	Case 1c	Case 1d
T1	1.000	1.000	1.000	1.000	1.000
T2	0.962	0.962	0.962	0.962	0.962
N1	0.962	0.962	0.962	0.962	0.962
N2	0.962	0.939	0.939	0.939	0.939
N3	0.961	0.962	0.962	0.962	0.962
N4	0.950	0.961	0.961	0.961	0.961
N5	0.939	0.950	0.950	0.950	0.950
N6	0.937	0.937	0.937	0.938	0.938
N7	0.937	0.937	0.937	0.937	0.937
N8	0.936	0.936	0.936	0.936	0.937
N9	0.928	0.928	0.928	0.928	0.929
N10	0.918	0.918	0.918	0.918	0.918
N11	0.908	0.908	0.908	0.908	0.908
N12	0.907	0.907	0.907	0.907	0.908
N13	0.898	0.898	0.898	0.898	0.899
N14	0.888	0.888	0.889	0.889	0.889
N15	0.879	0.878	0.878	0.878	0.879
N16	0.878	0.877	0.877	0.877	0.878

N17	0.877	0.875	0.875	0.876	0.876
N18	0.876	0.875	0.875	0.875	0.876
N19	0.875	0.876	0.876	0.876	0.877
N20	0.875	0.876	0.876	0.876	0.876
N21	0.875	0.875	0.876	0.876	0.876
N22	0.875	0.875	0.875	0.876	0.876
N23	0.874	0.875	0.875	0.875	0.876
N24	0.874	0.879	0.879	0.879	0.88
N25	0.876	0.875	0.875	0.876	0.876
N26	0.875	0.875	0.875	0.875	0.875
N27	0.875	0.874	0.874	0.875	0.875
N28	0.875	0.874	0.874	0.874	0.875
N29	0.871	0.871	0.871	0.871	0.872
N30	0.871	0.863	0.863	0.863	0.864
N31	0.870	0.855	0.855	0.855	0.856
N32	0.863	0.871	0.871	0.871	0.871
N33	0.862	0.870	0.871	0.871	0.871
N34	0.862	0.862	0.862	0.863	0.863
N35	0.862	0.862	0.862	0.862	0.863
N36	0.862	0.862	0.862	0.862	0.863
N37	0.855	0.862	0.862	0.862	0.863
N38	0.855	0.855	0.855	0.855	0.856
N39	0.855	0.855	0.855	0.855	0.856
N40	0.847	0.848	0.848	0.848	0.849
N41	0.840	0.840	0.840	0.841	0.841
N42	0.839	0.840	0.840	0.840	0.841
N43	0.839	0.839	0.839	0.840	0.840
N44	0.839	0.839	0.839	0.839	0.84
N45	0.838	0.838	0.838	0.839	0.839

N46	0.838	0.838	0.838	0.839	0.839
N47	0.833	0.833	0.834	0.834	0.835
N48	0.820	0.820	0.820	0.821	0.821
N49	0.814	0.814	0.814	0.814	0.815
N50	0.807	0.807	0.808	0.808	0.809
N51	0.801	0.801	0.801	0.802	0.803
N52	0.795	0.795	0.795	0.796	0.797
N53	0.789	0.790	0.790	0.79	0.791
N54	0.784	0.784	0.784	0.785	0.786
N55	0.776	0.776	0.776	0.777	0.778
N56	0.768	0.768	0.768	0.769	0.770
N57	0.759	0.760	0.760	0.760	0.762
N58	0.755	0.755	0.756	0.756	0.757
N59	0.754	0.755	0.756	0.756	0.757
N60	0.752	0.751	0.752	0.752	0.754
N61	0.751	0.748	0.748	0.749	0.750
N62	0.749	0.744	0.744	0.745	0.746
N63	0.748	0.740	0.740	0.741	0.743
N64	0.748	0.737	0.737	0.738	0.739
N65	0.747	0.733	0.734	0.735	0.736
N66	0.753	0.730	0.731	0.732	0.733
N67	0.751	0.728	0.728	0.729	0.731
N68	0.749	0.754	0.754	0.755	0.756
N69	0.747	0.752	0.752	0.753	0.754
N70	0.746	0.751	0.751	0.752	0.753
N71	0.745	0.749	0.75	0.75	0.751
N72	0.745	0.749	0.749	0.75	0.751
N73	0.745	0.748	0.748	0.749	0.750
N74	0.746	0.748	0.748	0.749	0.750

N75	0.745	0.753	0.753	0.754	0.755
N76	0.744	0.751	0.751	0.752	0.753
N77	0.744	0.749	0.749	0.750	0.751
N78	0.743	0.747	0.747	0.748	0.749
N79	0.744	0.746	0.746	0.747	0.748
N80	0.744	0.745	0.745	0.746	0.747
N81	0.744	0.746	0.746	0.747	0.748
N82	0.744	0.746	0.746	0.747	0.748
N83	0.755	0.745	0.745	0.746	0.747
N84	0.751	0.745	0.745	0.746	0.747
N85	0.747	0.744	0.745	0.745	0.746
N86	0.743	0.744	0.744	0.745	0.746
N87	0.740	0.744	0.744	0.745	0.746
N88	0.736	0.724	0.725	0.726	0.728
N89	0.733	0.725	0.725	0.726	0.728
N90	0.730	0.725	0.725	0.726	0.728
N91	0.727	0.744	0.744	0.745	0.746
N92	0.725	0.744	0.744	0.745	0.746
N93	0.724	0.744	0.744	0.745	0.746
N94	0.724	0.744	0.744	0.745	0.746
N95	0.722	0.722	0.723	0.724	0.726
N96	0.715	0.715	0.715	0.717	0.719
N97	0.713	0.714	0.714	0.715	0.717
N98	0.709	0.710	0.710	0.712	0.714

Table B5: Node Voltages in p.u. after Simulation, Scenario 2

Nodes	V Base	Case 2a	Case 2b	Case 2c	Case 2d	Case 2e	Case 2f
T1	1	1	1	1	1	1	1
T2	0.962	0.963	0.964	0.966	0.966	0.967	0.967
N1	0.962	0.963	0.964	0.966	0.966	0.967	0.967
N2	0.962	0.963	0.964	0.966	0.966	0.966	0.966
N3	0.961	0.963	0.964	0.966	0.966	0.966	0.966
N4	0.95	0.952	0.954	0.957	0.958	0.958	0.959
N5	0.939	0.942	0.944	0.948	0.949	0.95	0.952
N6	0.937	0.94	0.943	0.947	0.948	0.949	0.951
N7	0.937	0.939	0.942	0.946	0.947	0.948	0.95
N8	0.936	0.939	0.941	0.946	0.947	0.948	0.95
N9	0.928	0.932	0.935	0.941	0.942	0.943	0.946
N10	0.918	0.922	0.926	0.933	0.935	0.937	0.94
N11	0.908	0.913	0.917	0.926	0.928	0.93	0.934
N12	0.907	0.912	0.917	0.925	0.928	0.929	0.934
N13	0.898	0.904	0.909	0.919	0.922	0.924	0.929
N14	0.888	0.895	0.901	0.912	0.915	0.918	0.924
N15	0.879	0.886	0.893	0.906	0.909	0.912	0.918
N16	0.878	0.885	0.891	0.905	0.908	0.911	0.917
N17	0.877	0.884	0.89	0.904	0.907	0.91	0.916
N18	0.876	0.883	0.889	0.903	0.906	0.909	0.915
N19	0.875	0.883	0.889	0.902	0.905	0.908	0.915
N20	0.875	0.883	0.889	0.902	0.905	0.908	0.915
N21	0.875	0.883	0.889	0.902	0.905	0.908	0.915
N22	0.875	0.882	0.888	0.902	0.905	0.908	0.914
N23	0.874	0.882	0.888	0.901	0.904	0.907	0.914
N24	0.874	0.882	0.888	0.901	0.904	0.907	0.914

N25	0.876	0.883	0.889	0.902	0.906	0.908	0.915
N26	0.875	0.883	0.889	0.902	0.905	0.908	0.915
N27	0.875	0.883	0.889	0.902	0.905	0.908	0.915
N28	0.875	0.883	0.889	0.902	0.905	0.908	0.915
N29	0.871	0.879	0.886	0.9	0.904	0.907	0.915
N30	0.871	0.879	0.885	0.9	0.904	0.907	0.914
N31	0.87	0.879	0.885	0.9	0.904	0.907	0.914
N32	0.863	0.872	0.879	0.895	0.899	0.902	0.911
N33	0.862	0.871	0.879	0.895	0.899	0.902	0.91
N34	0.862	0.871	0.878	0.894	0.898	0.902	0.91
N35	0.862	0.871	0.878	0.894	0.898	0.902	0.91
N36	0.862	0.871	0.878	0.894	0.898	0.902	0.91
N37	0.855	0.865	0.873	0.89	0.894	0.898	0.908
N38	0.855	0.865	0.872	0.89	0.894	0.898	0.907
N39	0.855	0.864	0.872	0.89	0.894	0.898	0.907
N40	0.847	0.858	0.867	0.885	0.89	0.894	0.904
N41	0.84	0.851	0.861	0.881	0.886	0.891	0.902
N42	0.839	0.851	0.86	0.88	0.885	0.89	0.901
N43	0.839	0.85	0.859	0.88	0.885	0.889	0.9
N44	0.839	0.85	0.859	0.879	0.884	0.889	0.9
N45	0.838	0.85	0.859	0.879	0.884	0.889	0.9
N46	0.838	0.849	0.858	0.879	0.884	0.888	0.899
N47	0.833	0.845	0.855	0.877	0.882	0.887	0.899
N48	0.82	0.833	0.844	0.869	0.875	0.881	0.895
N49	0.814	0.828	0.839	0.865	0.872	0.878	0.893
N50	0.807	0.822	0.834	0.862	0.869	0.875	0.891
N51	0.801	0.817	0.829	0.858	0.866	0.872	0.889
N52	0.795	0.811	0.825	0.855	0.863	0.87	0.887
N53	0.789	0.806	0.82	0.852	0.86	0.868	0.886

N54	0.784	0.801	0.816	0.849	0.858	0.865	0.884
N55	0.776	0.795	0.81	0.846	0.855	0.864	0.885
N56	0.768	0.788	0.805	0.843	0.853	0.862	0.885
N57	0.759	0.781	0.799	0.84	0.851	0.861	0.886
N58	0.755	0.777	0.795	0.836	0.847	0.857	0.882
N59	0.754	0.775	0.793	0.835	0.846	0.856	0.881
N60	0.752	0.774	0.792	0.833	0.844	0.854	0.88
N61	0.751	0.772	0.791	0.832	0.843	0.853	0.878
N62	0.749	0.771	0.789	0.831	0.842	0.852	0.877
N63	0.748	0.77	0.789	0.83	0.841	0.851	0.876
N64	0.748	0.77	0.788	0.83	0.841	0.851	0.876
N65	0.747	0.769	0.788	0.829	0.84	0.85	0.876
N66	0.753	0.775	0.793	0.834	0.845	0.855	0.88
N67	0.751	0.773	0.791	0.832	0.843	0.853	0.878
N68	0.749	0.771	0.789	0.83	0.841	0.851	0.877
N69	0.747	0.769	0.787	0.829	0.84	0.85	0.875
N70	0.746	0.768	0.786	0.828	0.839	0.849	0.874
N71	0.745	0.767	0.786	0.827	0.839	0.849	0.874
N72	0.745	0.767	0.785	0.827	0.838	0.848	0.873
N73	0.745	0.767	0.785	0.827	0.838	0.848	0.873
N74	0.746	0.768	0.786	0.828	0.839	0.849	0.874
N75	0.745	0.767	0.785	0.827	0.838	0.848	0.873
N76	0.744	0.766	0.784	0.826	0.837	0.847	0.873
N77	0.744	0.766	0.784	0.826	0.837	0.847	0.872
N78	0.743	0.766	0.784	0.826	0.837	0.847	0.872
N79	0.744	0.766	0.785	0.826	0.838	0.848	0.873
N80	0.744	0.766	0.784	0.826	0.837	0.847	0.873
N81	0.744	0.766	0.784	0.826	0.837	0.847	0.873
N82	0.744	0.766	0.784	0.826	0.837	0.847	0.872

N83	0.755	0.778	0.797	0.841	0.853	0.863	0.89
N84	0.751	0.775	0.795	0.842	0.854	0.866	0.894
N85	0.747	0.773	0.794	0.843	0.856	0.868	0.899
N86	0.743	0.77	0.792	0.844	0.858	0.871	0.904
N87	0.74	0.768	0.791	0.846	0.86	0.874	0.909
N88	0.736	0.765	0.79	0.847	0.863	0.877	0.914
N89	0.733	0.763	0.789	0.849	0.865	0.88	0.919
N90	0.73	0.762	0.788	0.851	0.868	0.883	0.924
N91	0.727	0.76	0.788	0.853	0.871	0.887	0.93
N92	0.725	0.758	0.787	0.855	0.874	0.891	0.936
N93	0.724	0.758	0.787	0.855	0.873	0.891	0.935
N94	0.724	0.758	0.787	0.855	0.873	0.89	0.935
N95	0.722	0.757	0.787	0.857	0.877	0.895	0.942
N96	0.715	0.755	0.79	0.873	0.896	0.917	0.974
N97	0.713	0.756	0.792	0.879	0.903	0.925	0.985
N98	0.709	0.758	0.8	0.902	0.931	0.958	1.029

Table B5: Node Voltages in p.u. after Simulation, Scenario 3

Nodes	V Base	Case 3a	Case 3b	Case 3c	Case 3d
T1	1	1	1	1	1
T2	0.962	0.967	0.969	0.966	0.969
N1	0.962	0.967	0.969	0.966	0.969
N2	0.962	0.966	0.968	0.966	0.969
N3	0.961	0.966	0.968	0.966	0.968
N4	0.950	0.958	0.962	0.958	0.962
N5	0.939	0.949	0.956	0.949	0.956
N6	0.937	0.948	0.955	0.948	0.955
N7	0.937	0.947	0.954	0.947	0.954
N8	0.936	0.947	0.954	0.947	0.954

N9	0.928	0.942	0.951	0.942	0.951
N10	0.918	0.935	0.946	0.934	0.946
N11	0.908	0.927	0.941	0.927	0.941
N12	0.907	0.927	0.940	0.927	0.940
N13	0.898	0.921	0.936	0.920	0.937
N14	0.888	0.914	0.932	0.914	0.932
N15	0.879	0.908	0.928	0.907	0.928
N16	0.878	0.907	0.927	0.906	0.927
N17	0.877	0.906	0.926	0.905	0.926
N18	0.876	0.905	0.925	0.904	0.925
N19	0.875	0.904	0.924	0.904	0.925
N20	0.875	0.904	0.924	0.904	0.925
N21	0.875	0.904	0.924	0.904	0.924
N22	0.875	0.904	0.924	0.903	0.924
N23	0.874	0.903	0.923	0.903	0.924
N24	0.874	0.903	0.923	0.903	0.924
N25	0.876	0.904	0.925	0.904	0.925
N26	0.875	0.904	0.924	0.904	0.925
N27	0.875	0.904	0.924	0.904	0.925
N28	0.875	0.904	0.924	0.904	0.925
N29	0.871	0.902	0.925	0.902	0.925
N30	0.871	0.902	0.925	0.902	0.925
N31	0.870	0.902	0.924	0.902	0.925
N32	0.863	0.897	0.922	0.897	0.922
N33	0.862	0.897	0.922	0.896	0.922
N34	0.862	0.897	0.921	0.896	0.922
N35	0.862	0.897	0.921	0.896	0.922
N36	0.862	0.896	0.921	0.896	0.922
N37	0.855	0.893	0.920	0.892	0.920

N38	0.855	0.893	0.919	0.892	0.920
N39	0.855	0.892	0.919	0.892	0.920
N40	0.847	0.888	0.917	0.888	0.918
N41	0.840	0.884	0.915	0.883	0.916
N42	0.839	0.883	0.915	0.883	0.915
N43	0.839	0.883	0.914	0.882	0.915
N44	0.839	0.882	0.914	0.882	0.915
N45	0.838	0.882	0.914	0.881	0.914
N46	0.838	0.882	0.913	0.881	0.914
N47	0.833	0.88	0.914	0.879	0.915
N48	0.82	0.873	0.911	0.872	0.912
N49	0.814	0.869	0.91	0.868	0.911
N50	0.807	0.866	0.909	0.865	0.910
N51	0.801	0.863	0.908	0.861	0.908
N52	0.795	0.860	0.908	0.857	0.906
N53	0.789	0.857	0.907	0.853	0.904
N54	0.784	0.854	0.906	0.849	0.901
N55	0.776	0.85	0.906	0.844	0.897
N56	0.768	0.846	0.905	0.838	0.893
N57	0.759	0.840	0.902	0.831	0.888
N58	0.755	0.836	0.898	0.828	0.885
N59	0.754	0.835	0.897	0.826	0.883
N60	0.752	0.834	0.895	0.825	0.882
N61	0.751	0.832	0.894	0.823	0.881
N62	0.749	0.831	0.893	0.822	0.879
N63	0.748	0.830	0.892	0.822	0.879
N64	0.748	0.830	0.892	0.821	0.878
N65	0.747	0.829	0.892	0.821	0.878
N66	0.753	0.834	0.896	0.826	0.883

N67	0.751	0.832	0.894	0.824	0.881
N68	0.749	0.831	0.893	0.822	0.879
N69	0.747	0.829	0.891	0.82	0.877
N70	0.746	0.828	0.89	0.819	0.877
N71	0.745	0.828	0.89	0.819	0.876
N72	0.745	0.827	0.889	0.818	0.876
N73	0.745	0.827	0.889	0.818	0.876
N74	0.746	0.828	0.89	0.819	0.876
N75	0.745	0.827	0.889	0.818	0.875
N76	0.744	0.826	0.889	0.818	0.875
N77	0.744	0.826	0.889	0.817	0.875
N78	0.743	0.826	0.888	0.817	0.875
N79	0.744	0.827	0.889	0.818	0.875
N80	0.744	0.826	0.889	0.817	0.875
N81	0.744	0.826	0.889	0.817	0.875
N82	0.744	0.826	0.889	0.817	0.875
N83	0.755	0.900	0.828	0.885	0.885
N84	0.751	0.897	0.825	0.882	0.882
N85	0.747	0.830	0.893	0.821	0.879
N86	0.743	0.827	0.890	0.818	0.876
N87	0.740	0.827	0.890	0.818	0.876
N88	0.736	0.821	0.884	0.811	0.870
N89	0.733	0.818	0.882	0.808	0.867
N90	0.730	0.815	0.879	0.806	0.864
N91	0.727	0.812	0.877	0.803	0.862
N92	0.725	0.810	0.875	0.801	0.860
N93	0.724	0.810	0.874	0.800	0.860
N94	0.724	0.808	0.873	0.798	0.858
N95	0.722	0.805	0.870	0.795	0.854

N96	0.715	0.800	0.866	0.790	0.850
N97	0.713	0.798	0.864	0.789	0.849
N98	0.709	0.794	0.860	0.785	0.845