

Voltage Stability Improvement of Balanced Radial Distribution Networks

A Dissertation submitted in fulfillment of the requirements for the Degree
of

MASTER OF ENGINEERING *in* **Power Systems**

Submitted by

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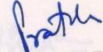
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I hereby certify that the work which is presented in a dissertation entitled, "**Voltage Stability Improvement of Balanced Radial Distribution Networks**", in partial fulfillment of the requirements for the award of the degree of Master of Engineering in Power Systems, submitted to Electrical & Instrumentation Engineering Department of Thapar University, Patiala is as authentic record of my own work carried under the supervision of Ms. Suman Bhullar. It refers others researcher's work which are duly listed in the reference section. The matter contained in this dissertation has not been submitted, neither in part nor in full to any other degree to any other university or institute except as reported in the text and references.

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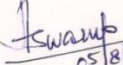
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NOMENCLATURE

Main symbols and notations used in this study are listed below.

P_{Loss}	Total real power losses
Q_{Loss}	Total reactive power losses
P_{net}	Total active Power Generation
Q_{net}	Total reactive Power Generation
P_{Load}	Total active Load
Q_{Load}	Total reactive Load
V	Voltage of bus
V_j^{min}	Minimum voltage limit
V_j^{max}	Maximum voltage limit
I_j^{SC}	Short circuit current
I	Branch current
br	Total number of branches
R	Branch resistance
X	Branch reactance
Z	Impedance of branch
SI	Stability index
$n1$	Sending end node
$n2$	Receiving end node
P	Active power load
Q	Reactive power load
kk	Branch number
i	Iteration
j	Bus number
$P_{t+1,eff}$	Effective real power delivered beyond the node 't+1'
$Q_{t+1,eff}$	Effective reactive power delivered beyond the node 't+1'

LIST OF ABBREVIATIONS

RDN	-	Radial Distribution Network
DG	-	Distributed Generation
CIGRE	-	International Council on Large Electric Systems
EPRI	-	Electric Power Research Institute
IEA	-	International Energy Agency
LCOE	-	Levelled Cost of Electricity
EPBT	-	Energy Payback Time
VSI	-	Voltage Stability Index
GA	-	Genetic Algorithm
PSO	-	Particle Swarm Optimization
REPSO	-	Rank Evolutionary Particle Swarm Optimization
EPSO	-	Evolutionary programming in Particle Swarm Optimization
STATCOM	-	Static Synchronous Condenser
ABC	-	Artificial Bee Colony
CABC	-	Chaotic Artificial Bee Colony
SA	-	Simulated Annealing
LSF	-	Loss Sensitivity Factor
KCL	-	Kirchhoff's Current Law
KVL	-	Kirchhoff's Voltage Law
HSA	-	Harmony Search Algorithm

ABSTRACT

An approach for the optimal placement of DG and Capacitor of proper size in Radial distribution networks (RDNs) is presented. At the beginning of the Electrical Power system, the active and reactive power losses had been a greater challenge. Compensating the power of the system has become the prime area to improve the system stability. The Distributed Generator and Capacitor allocation problem involves determining the optimal placements and also the selection of the perfect size of the DG and capacitor. Load flow is performed at first to compute the actual losses of the system and voltages at different nodes without compensation called base case. In the proposed technique, the LSF (Loss sensitivity factor) is used to determine the optimal location of DG& capacitor. The optimal sizes of the DG and Capacitor have been determined by analytical approach. To justify the objective of the method after installing the DG and Capacitor, the load flow is performed again at the identified nodes. The proposed scheme is tested on standard 33 node and 69 node RDNs.

CHAPTER 1

INTRODUCTION

In this progressive era, Electricity is treated as the most convenient and clean form of energy. The modern day social substructure would not be viable without electricity. It is transmitted instantly at the rate of speed of light when switched on. The increasing consumption of electricity across the world reflects the importance of electrical energy. The optimum utilization of energy by consumers is only possible if there is a perfect distribution network. Our important aim is to make power system network reliable and as well as economically efficient. There are a number of challenges faced by the engineers to design a stable and economical Power system.

1.1 Electrical Power Systems

It is a network consisting of electrical equipment as shown in Fig. 1.1. It mainly comprises of generation, transmission, sub-transmission, and distribution. Generation and transmission are referred as the bulk power supply and the other two parameters are referred as the release of electric power to the consumers.

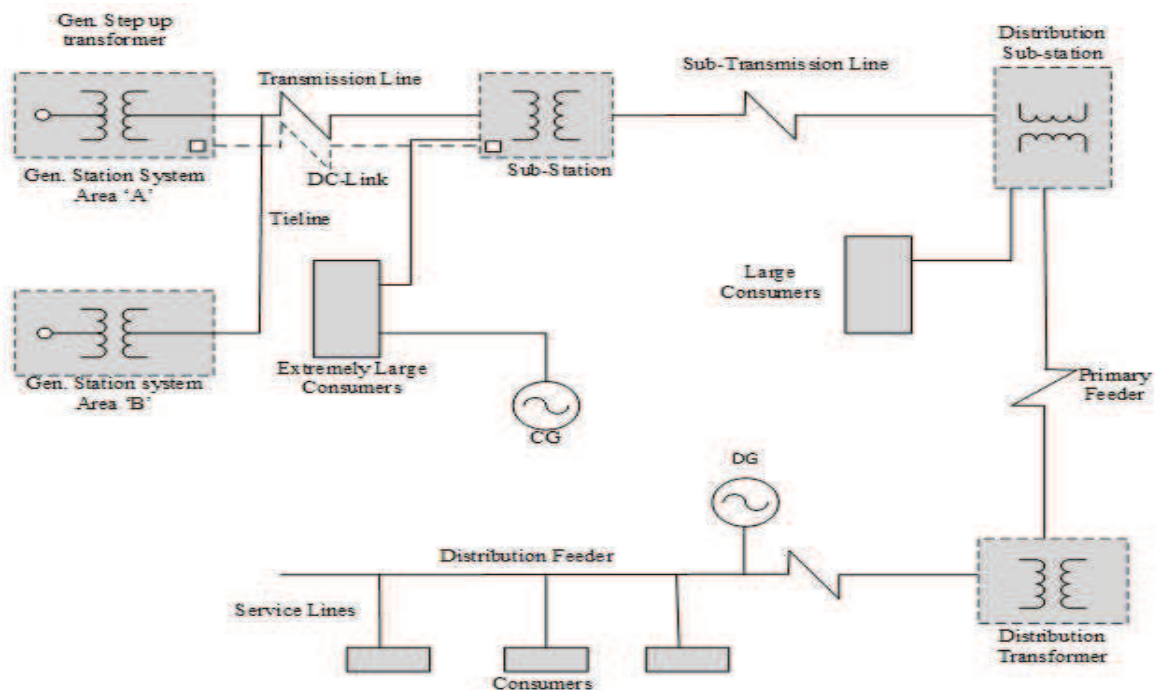


Fig 1.1 Schematic diagram of Electrical Power Network

1.2 Distribution of Power

The distribution system is the interface between the utility side and the load side.

It incorporates:

- Sub-transmission networks, usually in the voltage range of 33 kV and 220 kV, which is used to deliver energy to distribution substations.
- The distribution substation is used to alter the electrical energy to a lower primary voltage level for local distribution.
- Primary circuits of feeders operate in the range of 11 kV - 33 kV.
- Distribution transformers usually installed near the consumer sites, which are used to transform the primary voltage to the secondary voltage, i.e. 230/400 V.
- Service lines transfer the power of secondary networks to the consumer end at a voltage of 400/230 V \pm 6%.

As we know, operating frequency in India is 50 Hz. There is some special voltage level, such as 25 kV is used for traction in India. “Standard voltages, frequencies and their range of variation in distribution system have been specified by IS: -12360-1988 in India [36]”. Distribution at high voltage level has been done with the help of three-phase, single-phase or single wire earth return system. In short, it is also known as SWER. This type of system has been found successful in largely rural areas. It is a reliable system and expenses are considerably reduced in this system. Most of the losses occur during the distribution of electricity. About seventy five percent of the overall system losses take place during distribution. As per official records, transmission and distribution losses are recorded as 28%. Distribution losses are high because of lack of investment in the distribution systems. The overloaded system requires a reactive power support. Distribution side directly affects the consumer. The efficiency of the distribution system is nearly equal to 20%, including the consumer side, which is extremely poor. Distribution of voltage at a low level can be three phase four wire, single phase, three phase three wire or single phase three wire system. The main function is to provide electric power to individual consumers. Distribution is mainly done with the help of distribution networks as discussed above. It consists of distribution substation, primary distribution feeder distribution transformer, distributors and service mains.

1.3 Basic Distribution Systems

There are six basic distribution systems used by the utilities:-

- a) Radial
- b) Primary Loop
- c) Primary Selective
- d) Secondary Selective
- e) Spot Network
- f) Grid Network

1.3.1 Radial System

A system, which is connected to only one source of supply, is called as Radial system as shown in Fig. 1.2. In such system, primary feeders used to take energy from the substation and supply power to the associated loads with the help of sub-feeders and sideward branches. Such type of systems is not used in the densely populated area. One major drawback of this system is if any feeder gets disconnected from the mains, colligated customers would not receive an electrical supply as no other option is available to provide supplies to the transformer. Overhead line fault, Transformer breakdown and underground cable fault are possibilities of interruption in the radial system. Failure rates of transformer and feeders are finite and such types of interruption are expected and can be predicted statistically. All these faults lead to long interruption. Reliability is lower and hence suitable for small loads.

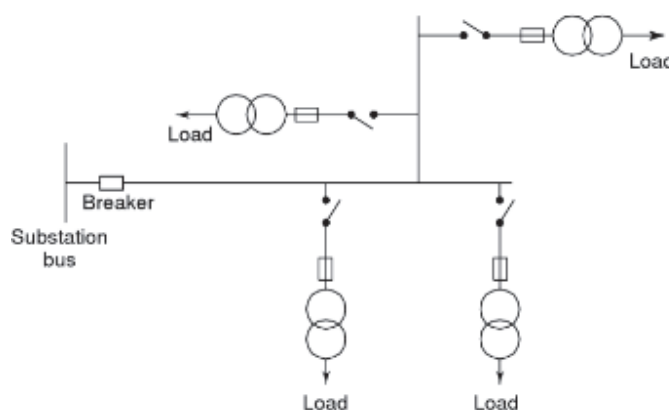


Fig 1.2 Radial Distribution Systems

1.3.2 Primary Loop

A much-needed refinement over a radial distribution network (RDN) is achieved by arranging a primary loop, which supplies power from two feeders as shown in Fig. 1.3. This is called as open ring system. The loop normally works with the sectionalizing switch open. If one feeder is under maintenance or out of service, the loop is still energised by the alternative one and it will not break the continuity of electric energy and consumers will not get affected. Each line of the loop has enough capacity to carry the entire load if any one of the feeders is out of service.

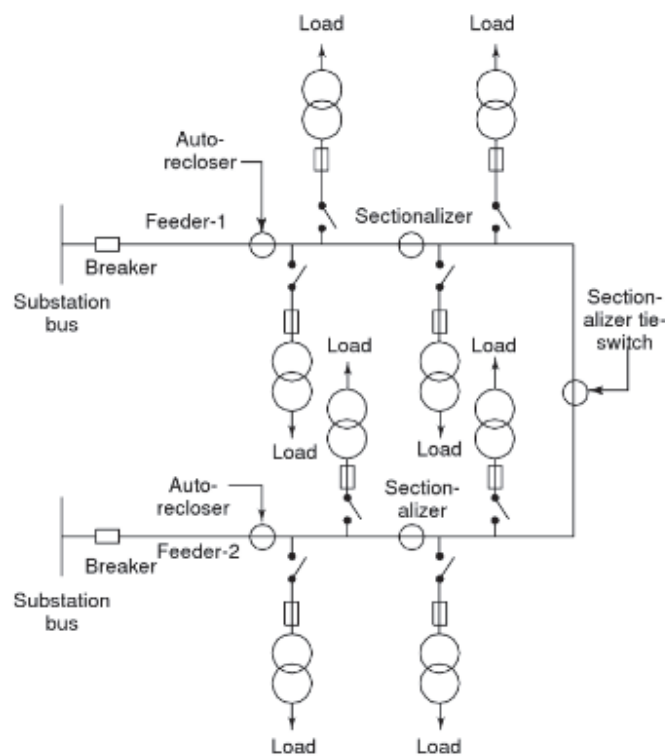


Fig 1.3 Primary Loop

1.3.3 Primary Selective

It handles the almost same equipment as that of the ring system. Transformers connected in the system have supply from two sources as shown in Fig. 1.4. If one feeder is out of service, shifting will be automatically done on the second feeder and the duration of the interruption is very small. Reliability of such type of arrangement is high. Such type of scheme is normally used where continuous supply is required, such as industrial loads.

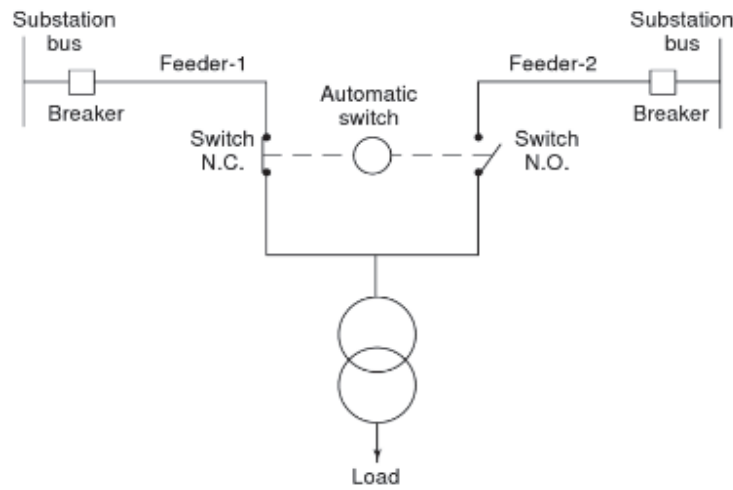


Fig 1.4 Primary Selective

1.3.4 Secondary Selective

This type of scheme needs two transformers, each fed from a different feeder as shown in the Fig. 1.5. This system is also called as Open Ring Main System. Such type of scheme is mainly used in hospitals and industrial plants. It is a more dependable system than primary selective. This is because of an extra redundancy of transformers.

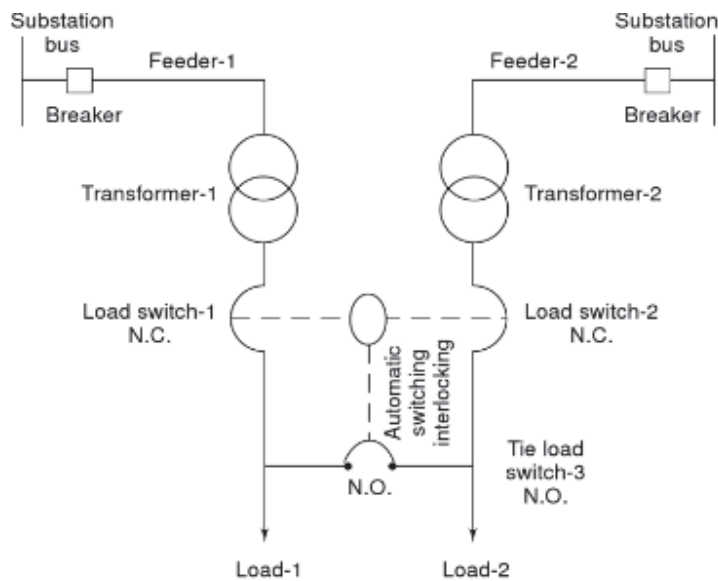


Fig 1.5 Secondary Selective

1.3.5 Spot Network

In this scheme, two or more transformer units are connected in parallel. Its behavior is similar to the closed ring system. It is clearly visible from the Fig. 1.6 that spot network bus continuously fed from the parallel networks. Such types of loads are generally used in the metropolitan areas or highly dense areas where continuous supply is required. Multiple numbers of feeders and transformers are used, so the system is highly reliable. Loads, which are served by spot network, require a high degree of reliability. Commercial buildings, malls, airports, hospitals, etc. having such types of loads are provided by spot networks. Consumers are free from temporarily and long duration disconnection of supply. It is almost non-existent.

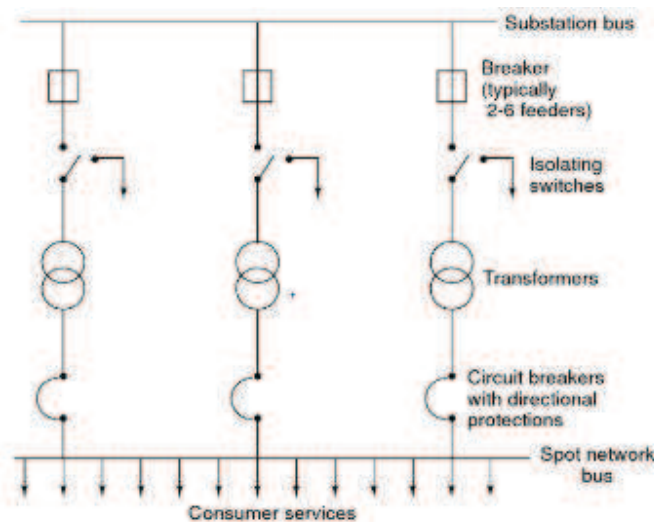


Fig 1.6 Spot Network

1.3.6 Grid Network

It provides the maximum operating resilience and reliability amidst all the systems. It is the most frugal and compelling scheme in serving the high capacity loads in metro cities. In this method, the consumer will not suffer any disconnection of supply, even if the feeder is under schedule maintenance. Voltage regulation is enhanced due to the fact that power fed to the consumers through different transformers those are operating in parallel as shown in Fig. 1.7. The grid can sustain sudden changes in the load and disturbances related to starting off the large motor, etc. Grid network is amply stiff and a defect in the single unit doesn't exceed voltage limits of sensitive loads.

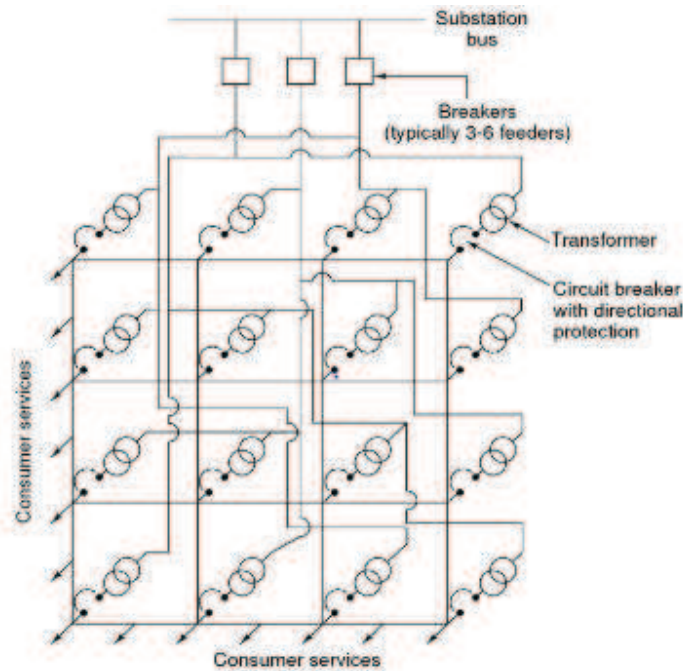


Fig 1.7 Grid Network

1.4 Distributed Generation

Dispersed generation is a source of electric energy colligated straight to the network of distribution side or meter installed at the consumer site. It is also termed as energy generation at low scale. It is also used as to get rid of expansion of new networks. Expansion of networks is required to support the new load areas of the consumers. It can be used as an alternative source of energy for homes, commercial and industrial purposes. There are various definitions of DG as illustrated by different organizations. “EPRI (Electric Power Research Institute), IEA (International Energy Agency) and CIGRE (International Conference on large High Voltage Electric Systems)” are the few organizations who presented the definition of the dispersed generator. Distributed generation is a methodology, which is used in various small-scale technologies in order to generate electricity up to the end consumers of energy. Generally, these technologies comprise modular generators, which give a lot of potential benefits. In comparison to traditional power generators, in most of the cases, distributed generators deliver higher power, reliability, lower-cost electricity and high security without affecting environmental values. Generally

Dispersed Generation has two levels:

- 1) Local Level Distributed generation
- 2) The End-point level Distributed generation.

Power generation plants at a local level normally consist of renewable energy based technologies, which are mostly site specific, like solar systems, hydrothermal plants, geothermal energy production, wind turbines, etc. However, these plants are less centralized and smaller in size in comparison to the traditional power plants. They are more reliable, cost effective and more energy efficient. In addition to other advantages over larger traditional plants, these local level DG plants are eco-friendly and produce energy without disrupting environmental condition.

1.4.1 Solar Power

Photovoltaic is the most significant solar technology in the field of solar power distributed generation which employs solar cells that are generally assembled into solar panels in order to transform the energy of sunlight into electricity. Photovoltaic systems range from residential, distributed as well as commercial rooftop, to large scale photovoltaic power stations. Crystalline silicon is one of the most predominant PV technologies, whereas thin-film solar cell technology comprises only 10 percent of the global photovoltaic distribution. By improving its conversion efficiency of sunlight to electricity, not only, the installation cost/watt has reduced, but also its Levelled Cost of Electricity (LCOE) and Energy Payback Time (EPBT) has reduced.

1.4.2 Wind Power

Wind turbines can be used as a resource for distributed energy. They can be made at utility scale. This technology has low pollution, low maintenance, but has higher costs as compared to other energy sources. As compared to solar, wind energy is non-dispatchable and variable. Wind towers have a better-operating safety, but due to high winds, it has considerable insurable liabilities too.

1.4.3 Hydro Power

Power generation using hydro-electricity is one of the most widely used methods of renewable green energy. Next generation turbines can be organized in arrays in order to serve the basic requirement of energy on a commercial, residential, municipal, industrial, or even regional scale. Micro-hydro based kinetic generators neither need dams nor impoundments since they use the

water motion, kinetic energy coming from the waves or flow. Hence there is no need of construction on the seabed or shoreline, which further simplifies the permitting procedure and reduces the environmental impacts.

1.5 Aim of Thesis Work:

This work introduces a DG and Capacitor placement technique to enhance the Voltage stability and node voltage. It also explains about the decrease in the total real and reactive power loss of RDN. The main aim is to improve the voltage stability and node voltages, while maintaining specified limit of the voltage of nodes in the network by installing suitable rating of DG and Capacitor unit in the RDN with different arrangements. LSF is used to identify the site. The analytical method is used to identify the size of DG and capacitor.

1.6 Organization of the Thesis:

The organization of this thesis is as follows:-

Chapter-1 includes the overview of Distribution systems and distributed generation, aim and organization of the thesis.

Chapter-2 presents the review of research papers.

Chapter-3 explains the problem formulation.

- 1) Discussed Load Flow (Backward/Forward sweep method).
- 2) Discussed VSI.
- 3) Explained LSF.

Chapter-4 consists of the results of 33 node and 69 node RDNs.

Chapter-5 includes the conclusions of thesis work and future Scope.

References

Appendix-A shows the system data for the 33 node and 69 node RDNs.

CHAPTER 2

LITERATURE REVIEW

Acharya *et al.* [1] recommended a logical expression to estimate the ideal size and also suggested a useful algorithm to determine the ideal location for siting of DG. These expressions were based on the exact loss formula. Sizing and siting of dispersed generator regarding loss was examined clearly. The recommended technique was tested on the networks of different size and complexity.

Murthy and Kumar [2] mainly contributed how to determine the ideal location for siting of DGs. It was described with the help of sensitivity methods as well as they proposed a new VSI. Various index methods were compared that was used to identify the site for DG and as well as the size of the dispersed generator. The result showed the necessity of installing DG of suitable size at a suitable location.

Rau *et al.* [3] discussed a method of installing DGs in the Power system (i.e. Transmission, distribution, and sub-transmission) for reducing the active and reactive power losses as well as burdening on chosen lines. The method was implemented for the best possible siting of distributed generators to maximize the profits.

Nara *et al.* [4] used a tabu search algorithm for the siting of distributed generator to cut down the active and reactive power losses in the system. Various techniques like coordination/decomposition were introduced to implement the algorithm. It was found with the help of numerical examples that analytical results were better than Simulated Annealing (SA) method.

Pisica and Bulac [5] proposed a comparison between Genetic Algorithm (GA) and nonlinear optimization for sizing and optimal location of distributed generator. They used active power losses and investment costs as the objective function and implemented on the IEEE 69 node system. They discussed the necessity of placing the DG at the perfect location. Non-optimal location may increase the system losses.

Mao and Miu [6] discussed a new placement method to elevate the dependability of the distribution arrangement and minimize the real power and reactive power losses of the system by

an ideal placement of DG. The algorithm presented in the paper was graphical based and the method was more suitable for an unbalanced system with one or more than one DG units.

Bhumkittipich *et al.* [7] developed a new approach for the siting of DG in the RDN with the help of “Particle Swarm Optimization (PSO)”. The method was tested on 26 node RDN. Single DG placement was used to come across, the size of the distributed generator and its site which led to the maximum loss reduction.

Parizad *et al.* [8] presented two scenarios for an ideal siting of DG in the RDN. In the first method, the only active power loss was minimized. Optimal location and size were identified with the help of exact loss formula. The other method was used the Voltage Stability Index to find the optimum location.

Helal *et al.* [9] used the GA as an optimization technique. The main objective was to identify the optimal node for placement of DG to minimize the total losses with the acceptable voltage limit. The algorithm was applied to 13 bus network and the results indicated that losses were minimised.

Reddy *et al.* [10] proposed ideal siting of capacitors in RDN with the help of meta-heuristic technique i.e. Cuckoo search algorithm. The advantages of placing a capacitor were to minimize losses and improved voltage profile.

Ghosh *et al.* [11] proposed an easy technique for sizing and placement of DG. Formulation of load flow had been done with the help of Newton-Raphson as well as conventional iterative search technique implemented on three different bus systems. The objectives were to reduce losses and cost. A weighting factor was also discussed in the paper, which was used to balance loss and cost factors. Optimal placement and sizing provided the significant improvement in the results.

Zareiegovar *et al.* [12] defined a constrained optimization problem for an ideal siting and sizing of DG in the RDN. The objectives were to boost the voltage of the system and the voltage stability of the system. The objectives were achieved by minimizing losses of the system. These three parameters were formulated as the objective function. A 69 node system was considered as

the system. The optimization problem of the case study was solved with the help of PSO and compared with the results of previous research.

Chen *et al.* [13] introduced an interface between DGs and RDN. They presented a new method for constructing a sensitivity matrix which was used for the computation of power flow with multiple types of DGs. With the help of the method presented in the paper, the impacts of DGs on the system voltage stability were studied.

Atwa *et al.* [14] presented a GA based multi-objective optimization technique used for the best possible allocation of various types of dispersed generator units. The main aim was to maximize the savings of the system. The rural areas distribution system was considered for the implementation of the technique. The technique showed an accuracy problem when eminence result was required still cost was effectively reduced.

Singh and Goswami [15] presented a new technique based on nodal pricing. It was used for the allocation of DG for a decrement in the loss and for the betterment of the voltage level. The study was implemented for time variant and time invariant loads. The result indicated that small DG units were more beneficial when compared with larger DG units which were non-optimally located.

Jamian *et al.* [16] proposed a new formulation for placement of multi dispersed generator and sizing for RDN by using VSI. Several types of PSO algorithm were used to find out the optimal DG size. The output results were compared with REPSO, PSO and EPSO. The algorithm used was tested on 12 node and 69 node RDNs.

Griffin *et al.* [17] proposed a methodology for placement of dispersed fuel cell generators. They presented an algorithm to find the optimal placement of dispersed generator units on the power grid. The results showed the importance of placement of dispersed generator for the minimization of losses and maximization of the capacity savings.

Naik *et al.* [18] presented an analytical and convenient method for placement and sizing of the dispersed generator. The main objective was to minimize the active and reactive losses and with the help of analytical expression saving was computed. They first defined the size of DG and then selected the optimal node for placement. The results were obtained for the single and

multiple dispersed generator units. The 33 node and 69 node RDNs was used to implement the technique.

Biswas *et al.* [19] presented the ABC algorithm. The technique was used for the best possible settlement of DG. The main aspects of the paper were to minimize active power loss, variation in node voltage, voltage sag and as well as the cost of distributed generator. The multi-objective problem with the help of penalty function and weighting method approach was formulated and successfully implemented in 34 node system. The results were compared with the GA.

Muttaqi *et al.* [20] addressed the difficulties of improving the voltage profile by installing a DG at a suitable location and of suitable size. An analytical method was proposed based on algebraic equations to determine the location, size and operation of DG. A practical method was used in the paper to verify the analytical technique and test results.

Sangeetha and Jalendiran [21] proposed a Harmony Search Algorithm (HSA) which was derived from the musical process. The “Loss Sensitivity Index” approach was used to identify the ideal location for placement of DG. The algorithm used on the optimal location to curtail the loss and improve the voltage level. To check the performance of the technique the outcomes were compared with the other techniques. The study was implemented on the 33 node RDN.

Safavi *et al.* [22] discussed the problems regarding placement and sizing of DG with the time-varying loads. GA and HSA were used as optimization techniques and their results were compared. The implementation of the technique was executed on the 33 node RDN. As indicated in the paper, HSA was more efficient than GA.

Singh *et al.* [23] addressed the effect of alteration of loads with frequency and voltage for optimal allocation of DG and its sizing. Frequency can't be controlled locally so that they had made certain assumptions and defined the range of frequency. The main objective was to minimize losses of the system and improve the voltage profile with variation in loads using GA as an optimization technique.

Meghana *et al.* [24] presented a second order power flow sensitivity method, which helped in illustrating the nonlinear behavior of power losses. That method increased the speed of the

solution. Various types of DG were used to figure out the accuracy & speed of the propounded method.

Ghosh and Sherpa [25] presented an efficient and new load flow technique of RDN with minimum data required. In this method, node number and branch number need not be sequential. The proposed method used the simple equation to evaluate the voltage magnitude and can be implemented on the composite load modelling.

Ghosh and Das [26] presented an efficient method of load flow for solving the radial networks. The presented method comprises only the calculation of an algebraic expression of receiving end voltages. The discussed load flow was very efficient. The usefulness of the discussed method was shown with the help of different system.

Hussain and Roy [27] proposed a new population-based technique named as modified-ABC algorithm for the settlement of DG to lower the active power dissipation, improves the level of voltage, improves supply quality and lowers the line loss and environmental impacts in the RDN. The modification was done in the neighboring search of ABC algorithm. The technique was implemented on the 33 node arrangement and implemented in MATLAB.

Kumar and Selvan [28] proposed a new methodology for improvement of voltage stability margin. The size of DG unit was identified with the help of optimization of the multiobjective index. The presented method was tested on Indian systems. It was found that implemented method was very effective on 11 kV, 25 node arrangements.

Mohandas *et al.* [29] presented a Chaotic Artificial Bee Colony (CABC) algorithm which was used to get the size of DG to be placed. Type-one distributed generator was used, which injected real active power to improve the power loss in the system. Constant power and voltage dependent load models were considered to check the accuracy of the algorithm. The algorithm was tested on the 38 node and 69 node RDNs.

Zheng and Kezunovic [30] presented an accurate stability index to rectify the voltage stability. The recommended Voltage Stability Index (VSI) had been tested with the integration of wind farms. STATCOM was used to show its capability in improving voltage stability.

Chakravorty and Das [31] presented voltage stability study of RDN. A technique called VSI was proposed for finding the node, which was most delicate to voltage collapse. Composite load modelling was considered in the analysis of voltage stability. It was also verified that the solution presented of RDN was unique.

Reddy *et al.* [32] proposed minimization of loss in the RDN with the help of a hybrid system. Dispersed Generator, capacitor and combination of both were placed in the best possible location. The main purpose was to minimize the loss of the system. Genetic Algorithm was used as an optimization technique. The 33 node RDN was used to test the validity of the proposed technique.

Das [33] presented a GA-Fuzzy based method to identify the best possible locations of capacitors (fixed and switched type) to enhance the voltage of the system and maximizing the net savings of RDN. The fuzzy multi-objective function solution was solved with the help of GA. The effectiveness of the method was implemented on the 69 node RDN.

Rao [34] presented a hybrid approach that combined the reconfiguration of the network and placement of a capacitor with the help of Harmony Search Algorithm (HSA). The main objective was to minimize the power losses and improve the voltage level. The result obtained after the computational procedure was more efficient. The standard 16 node and 33 node RDNs was used for the implemented technique.

Bae [35] presented an analytical approach to identify the best possible location of capacitor and level of reactive compensation. The results showed that loss reduction was not the only benefit with the help of uncontrolled capacitor banks, but best reactive recompense level and total annual loss were explained with the help of mathematical equations.

CHAPTER 3

PROBLEM FORMULATION

The flow of the power from designated bus to the load bus is called as load flow analysis. Every load flow analysis has certain parameters, which should be satisfied to make load flow analysis feasible. These parameters are mentioned in the section 3.1:-

3.1 Bus Classification

Every load flow has a certain arrangement for the buses, which has certain characteristics. Mainly buses are classified into three types:-

- 1) Slack bus-It is also referred as reference bus. Such kind of bus has voltage magnitude and phase angle. Mainly substation buses are considered as slack bus and represented as $1\angle 0^\circ$ for the balanced distribution network
- 2) Generator bus-It is often called as PV bus. It has active power and voltage. In the load flow analysis of distribution network there is no use of PV bus, but in the case of DG placement, suitable nodes are considered as PV bus.
- 3) Load bus- Every load has active power and a reactive power component, that's the reason load bus is also known as PQ bus. In the distribution network, loads are in the form of complex power.

3.2 Objective Function

Power flow evaluation of radial configuration distribution network has two main objectives, first to maintain voltage level and voltage stability index (VSI) and second to minimize the net power loss.

$$\text{Min (F) = max (VSI)} \quad (3.1)$$

Where, F=objective function

3.2.1 Voltage Regulation

The voltage level of the nodes gradually decreases with the voltage drop. The large network has more voltage issues, which results in the form of the poor voltage level at the end nodes. The

first primary objective is to maintain the bus voltage at a certain safe level. This can be achieved by an analytical technique called as voltage sensitivity index [31].

3.2.2 Loss Minimization

The second primary objective is the loss minimization in the radial network. Branch power losses in the network depend on the branch current. The branch current depends on the current consumed by the load. Active and reactive branch loss is given in equation Eq. 3.2 and Eq. 3.3 respectively:-

$$P_{loss}(kk) = I^2(kk) \times R(kk) \quad (3.2)$$

$$Q_{loss}(kk) = I^2(kk) \times X(kk) \quad (3.3)$$

$$f = \min. \sum_1^{br} P_{loss}(kk) \quad (3.4)$$

Where,

P_{loss} = Real power loss

Q_{loss} = Reactive power loss

kk = branch number

I = branch current

br = total number of branches

R = Branch resistance

X = Branch reactance

3.2.3 Constraints

For every load flow analysis, there is certain margin, which restricts the network parameters, these are known as constraints. Some important constraints are mentioned below:-

3.2.3.1 Inequality Constraints

There are two inequality constraints, i.e.

a) Bus voltage constraint and b) Short circuit current constraint

- a) Bus voltage constraint – These are the limits up to which the bus voltage could vary. The Eq. 3.5 represents the higher and lower limit of the bus voltage

$$V_{(j)}^{min} \leq V_j^{bus} \leq V_{(j)}^{max} \quad (3.5)$$

Where,

V_j^{min} =Minimum voltage limit

V_j^{max} =Maximum voltage limit

j = Bus number

- b) Short circuit current – The branch current should not exceed the tolerable short circuit current limit otherwise circuit breaker may trip and isolate from the system.

$$I_j \leq I_j^{(SC)} \quad (3.6)$$

Where,

I_j = Branch current

I_j^{SC} =Short circuit current

3.2.3.1 Equality Constraints

Equality constraint of the system can be presented as power flow equation given in equation number.

$$\sum P_{net}^{bus} = \sum P_{load}^{bus} + \sum P_{Loss}^{br} \quad (3.7)$$

$$\sum Q_{net}^{bus} = \sum Q_{load}^{bus} + \sum Q_{Loss}^{br} \quad (3.8)$$

Where,

P_{net} = Total Active Power Generation

Q_{net} = Total Reactive Power Generation

P_{Load} =Total Active Load

Q_{Load} =Total Reactive Load

P_{Loss} = Total Active Power loss

Q_{Loss} = Total Reactive Power loss

br = Total number of branches

3.3 Load Flow Analysis

Load flow is a mathematical analysis which deals with several interconnected systems or subsystems of the network. Usually, power flow analysis includes line data and load data of the system. Single line representation is necessary to denote all the components present in the bus system and the calculation involves per unit value of the parameters. The foremost aim of the load flow is to determine the voltage magnitude and the phase angle of each bus present in the system. The active and the reactive power losses are also part of such analysis.

3.3.1 Backward and Forward Sweep

It is a new approach for load flow analysis, which involves the basic principles of Kirchhoff's Law. Initially, the load flow starts with a backward sweep, which is based on Kirchhoff's Current Law (KCL). Once the current at each node and in branch have been calculated, then the voltage at each node can be calculated using forward sweep. Forward sweep is based on Kirchhoff's Voltage Law (KVL). Backward/forward sweep is much faster than traditional load flow technique, that's why it is preferred for large bus networks. Some parameters necessary to assume before load flow analysis are mentioned below:-

- i) Distribution lines are transposed and working in balanced condition.
- ii) Load flow is working in the steady state condition and free from any transient situation.
- iii) No charging current due to the absence of the shunt capacitance
- iv) All the loads are constant power load
- v) No mutual coupling between lines.

3.3.2 Algorithm for Load Flow:-

Following steps are involved in backward/forward load flow technique for the balanced distribution network.

1. Read the line data, i.e. number of branches, sending end nodes, receiving end nodes and line impedance.
2. Read the load data, i.e. active and reactive power loads at each receiving end node.
3. Set the maximum number of iterations and the convergence factor ϵ .
4. Read the base MVA and kV rating of the network to convert different parameters in per unit value.

5. Initialize the line voltage as 1 p.u. for each bus.
6. Determine the load current at each node by the formula given below

$$I_{load}(j) = \frac{(P_{load}(j) - j \times Q_{load}(j))}{V(j)^*} \quad \text{Where } j = \text{node} \quad (3.9)$$

7. Apply backward sweep to calculate the branch current from the load current. In the case of the end node branch current and load current will be same for the radial network. Following equations are important for the backward sweep.

$$I_{branch}(kk) = I_{load}(kk + 1) \quad \text{where } kk = \text{branch} \quad (3.10)$$

$$I_{branch}(kk + 1) = I_{load}(kk + 1) + I_{branch}(kk) \quad (3.11)$$

8. Apply forward sweep to calculate the bus voltage at each node.

$$V_{node}(SE(kk)) = V_{node}(RE(kk)) + (R(kk) + jX(kk))I_{branch}(kk) \quad (3.12)$$

9. Check the convergence factor for every iteration. If it satisfies the condition break the loop else repeat the process with upgraded voltage magnitude.

$$\max |V_{node}^{i+1} - V_{node}^i| < \epsilon \quad \text{where } i = \text{iteration} \quad (3.13)$$

10. Calculate the Active and reactive power losses from the given formula

$$P_{loss}(kk) = I^2(kk) \times R(kk) \quad (3.14)$$

$$Q_{loss}(kk) = I^2(kk) \times X(kk) \quad (3.15)$$

3.4 Voltage Sensitivity Index (VSI)

It is a mathematical approach which helps to determine the weakest node of the RDN for which the chances of voltage collapse is higher. Voltage sensitivity gathers the node number, which has the least value after the formulation. Fig 3.1 represents a typical two-node system with load at receiving end and equation 1 represents the voltage sensitivity index of two node systems.

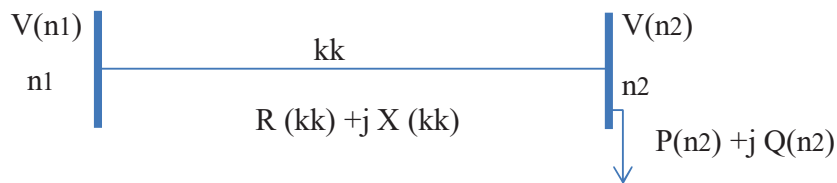


Fig 3.1 Equivalent circuit

$$SI(n2) = \{|V(n1)|^4 - 4.0\{P(n2) \times X(kk) - Q(n2) \times R(kk)\}^2 - 4.0\{P(n2) \times R(kk) + Q(n2) X(kk)\}|V(n1)|^2\} \quad (3.16)$$

Where,

SI = Stability index

V = Voltage at the node

n1 = Sending end node

n2 =Receiving end node

P = Active power load

Q = Reactive power load

R = Resistance of branch

X = Reactance of the branch

kk= branch number

3.5 Siting of Dispersed Generator

A sensitivity index method is used to determine the location of the DG. Proper location and sizing of the dispersed generator are necessary due to the fact that loss may overshoot the value of loss available at base case.

3.5.1 Types of DG:-

There are four most essential types of DG based on their uniqueness as explained in the different research papers:-

- Type-I DG
- Type-II DG
- Type-III DG
- Type-IV DG

Type -I Dispersed Generator is used to supply the active power in the system. Examples of type-I Dispersed Generator are Fuel cells, micro-turbines, which are further linked to the major grid using inverters etc.

Type-II DG is used to supply the reactive power in the system. Synchronous compensator such as DSTATCOM is a good example for type-II DG.

Type-III DG is used when the system requires the both real and reactive power. Mainly, Synchronous machine is the example of type-III distributed generator.

Type-IV DG is used to supply the active power in the system, but used to consume reactive power. Induction generators mostly used in the wind farms are falling in the type-IV category.

3.5.2 Advantages of Dispersed Generator are:-

- 1) Reduce losses in the distribution network by supplying additional load demand.
- 2) Decreases the thermal stress of the system. It is mainly due to the fact of overloaded SSs, Transformers and feeders.
- 3) It is used to provide the local load reliability or in other words, it can be used as an on-site standby system and used to supply power during emergency situations.
- 4) Useful in load management programs and helpful in peak load saving.
- 5) Used to maintain power system stability by supplying the required spinning reserve.

3.6 Siting of Capacitor

Capacitors are mainly used for the reactive power compensation in the distribution systems. The main intention is to diminish the system loss and perk up the voltage profile of the system within acceptable limits. The maximum profit of the system can be achieved when the location and size of capacitors are perfect. The difficulty is to find the site and the size of the capacitor to exploit the benefits of the capacitors related to the cost.

There are few factors associated with the placement of capacitors:-

- 1) Load variations
- 2) Type of capacitors- Switched or Fixed
- 3) Location of the capacitors
- 4) Cost of the capacitors

3.6.1 Benefits of Capacitor

- 1) Useful in enhancement of power factor.
- 2) Perk up the voltage of the system.
- 3) Curb the losses of the system.

3.7 Loss Sensitivity Factor (LSF)

It is one of the useful techniques to identify the node for siting of dispersed generator and capacitor. The LSF is used to find the best possible node in the system. The values of LSF will be arranged in the descending order. The node at which value of LSF is maximum is the most optimum node for the siting of DG and capacitor.

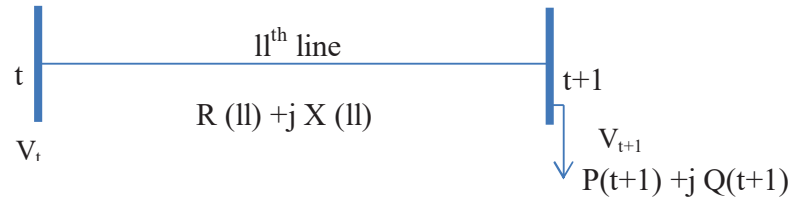


Fig 3.2 Line between 't' and 't+1' buses

The real line loss in the l^{th} line is specified as:-

$$P_{loss}[l] = \frac{(P^2[t+1] + Q^2[t+1])R[l]}{V[t+1]^2} \quad (3.17)$$

Similarly for,

$$Q_{loss}[l] = \frac{(P^2[t+1] + Q^2[t+1])X[l]}{V[t+1]^2} \quad (3.18)$$

After differentiating Eq. 3.17 and Eq. 3.18 with respect to change in real and reactive power. The loss sensitivity factor can be expressed as:-

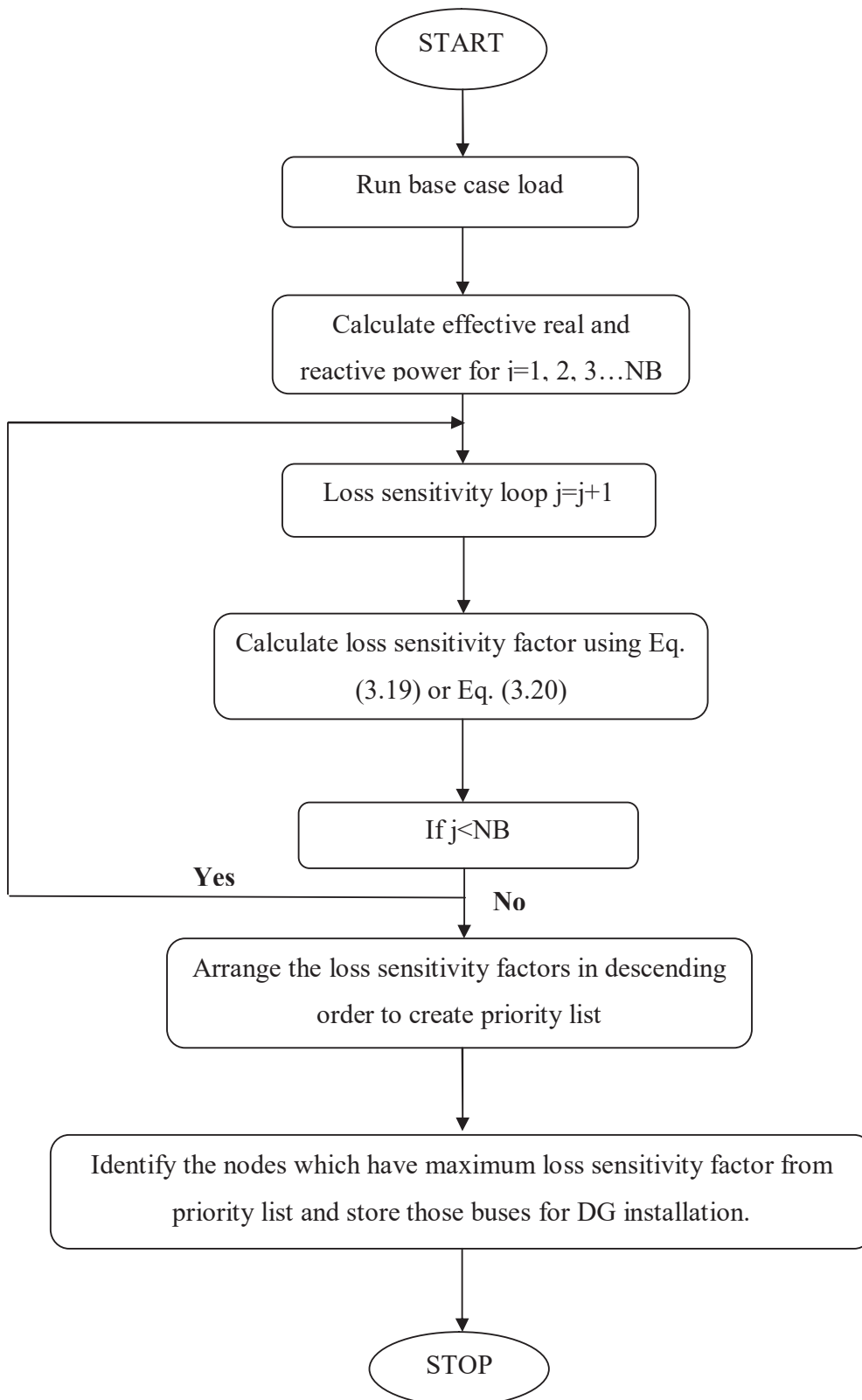
$$\frac{\partial P_{loss}(t, t+1)}{\partial Q} = \frac{2 * Q[t+1], eff \times R[l]}{|V[t+1]|^2} \quad (3.19)$$

$$\frac{\partial Q_{loss}(t, t+1)}{\partial P} = \frac{2 * P[t+1], eff \times X[l]}{|V[t+1]|^2} \quad (3.20)$$

$P_{t+1, eff}$ = Effective real power delivered beyond the node 't+1'

$Q_{t+1, eff}$ = Effective reactive power delivered beyond the node 't+1'

3.8 Flowchart for Siting of DG:-



3.9 Algorithm for Siting of Capacitor:-

- 1) Implement Load flow for the base case.
- 2) Calculate the values of active and reactive power losses.
- 3) Check the node at which voltage is minimum.
- 4) Check the node where Voltage sensitivity index is minimum.
- 5) Calculate Loss Sensitivity factor (LSF).
- 6) Arrange the values of LSF in descending order.
- 7) Consider the first three optimum outcomes from LSF.
- 8) Place the capacitor.

3.10 Algorithm for Siting of Capacitor and DG:-

- 1) Implement Load flow for the base case.
- 2) Calculate the values of active and reactive power losses.
- 3) Check the node at which voltage is minimum.
- 4) Check the node where Voltage sensitivity index is minimum.
- 5) Calculate Loss Sensitivity factor (LSF).
- 6) Arrange the values of LSF in descending order.
- 7) Consider the first three optimum outcomes from LSF.
- 8) Place the combined capacitor and DG on each node and different combinations of DG and capacitor at each node.
- 9) Check the result.

3.11 Steps for Sizing of DG and Capacitor

- 1) Run load flow for the base case.
- 2) Initially, Proceed with the steps of 10 kW/ kVAr.
- 3) Look for the value at which loss is minimum than the base case loss.
- 4) Further proceed to ensure the value at which loss is minimized abruptly.
- 5) Then vary in small steps of 1- 2 kW/ kVAr.
- 6) Find the range at which the loss starts decreasing and again starts increasing.
- 7) Check each value of that particular range.
- 8) Again implement the load flow with that value.
- 9) Obtain the best possible size.

CHAPTER-4

RESULTS

The overall thesis is based on single phase balanced distribution system of RDNs. The complete load flow analysis, including DG and capacitor placement process and used algorithm have been tested on the 33-node and 69- node RDNs. The arrangements of both the networks have been presented and examined with the help of DG, capacitor and DG plus capacitor. Substation Voltage is taken as 12.66 kV and base MVA is considered as 100 MVA for the system shown in Fig. 4.1 and Fig. 4.2.

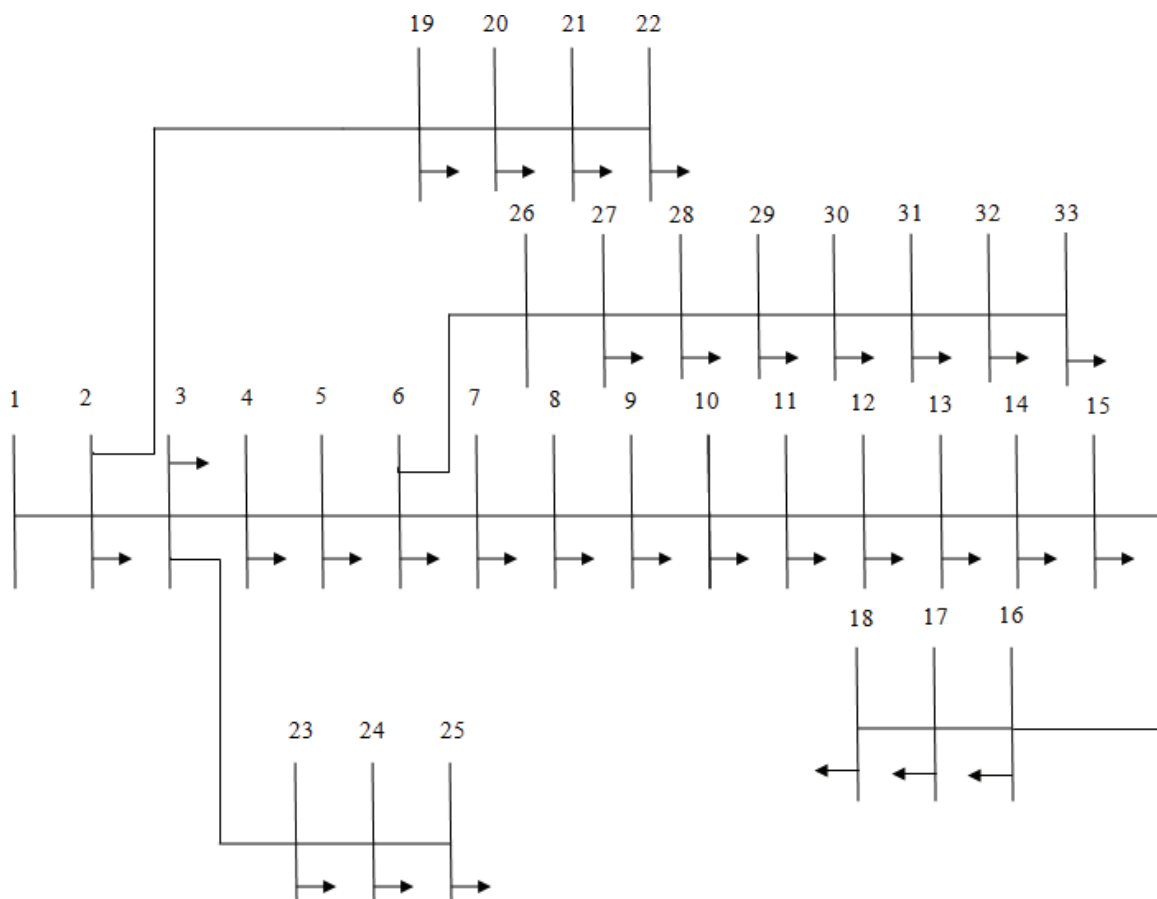


Fig. 4.1 33 node arrangement

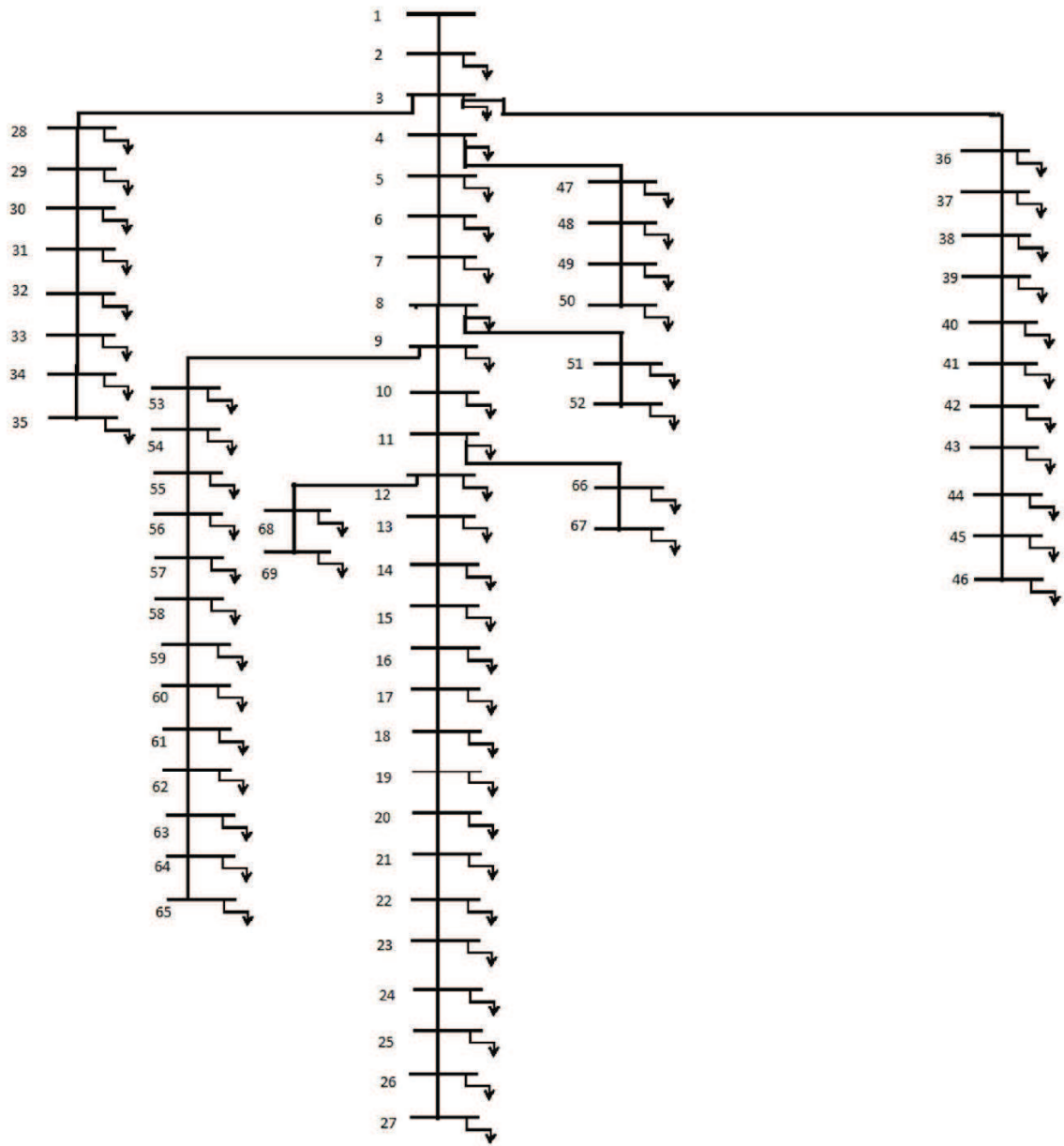


Fig. 4.2 69 node arrangement

4.1 For 69 Node

4.1.1 Case -1 With DG

Table 4.1: Performance analysis with DG in 69 node RDN

Case-1	Base Case	With DG	With DG	With DG
Optimal Node	–	61	64	62
Size of DG (kW)	–	1872	1650	1848
Active Power Loss (kW)	224.9219	83.1792	96.5456	84.6789
Reactive Power Loss (kVAr)	102.1295	40.5175	47.4478	41.3116
Minimum Voltage (node)	0.9092 (65)	0.9683 (27)	0.9669 (27)	0.9682 (27)
Minimum VSI (node)	0.6767 (65)	0.8789 (24)	0.8738 (25)	0.8784 (25)

Fig. 4.3 shows the Voltage profile Vs Node number for the base case and after implementation of DG at optimal nodes for 69 node RDN.

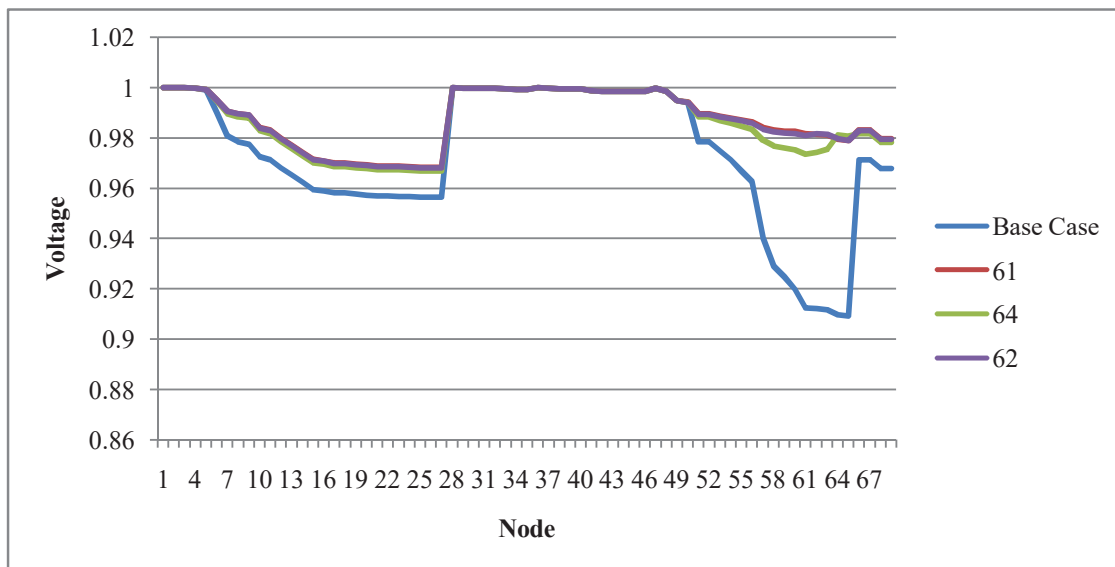


Fig. 4.3 Voltage Vs Node

Fig. 4.4 shows the VSI Vs Node number for the base case and after implementation of DG at optimal nodes for 69 node RDN.

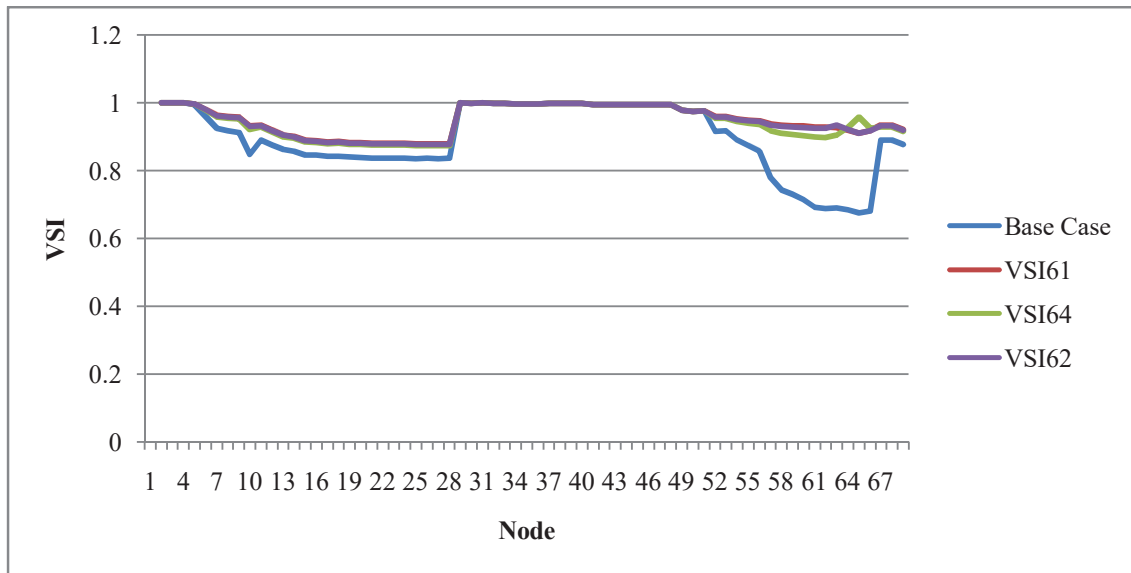


Fig. 4.4 VSI Vs Node

Fig. 4.5 shows the Power loss Vs Branch number for the base case and after implementation of DG at optimal nodes for 69 node RDN.

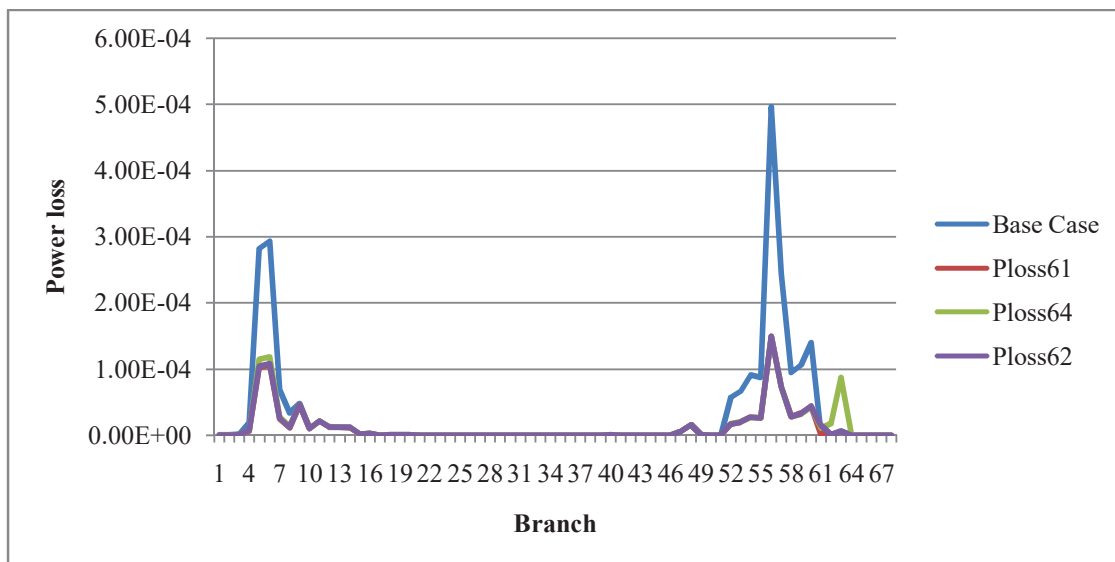


Fig. 4.5 Power loss Vs Branch

4.1.2 Case-2 With Capacitor

Table 4.2: Performance analysis with capacitor in 69 node RDN

Case-2	Base Case	With Capacitor	With Capacitor	With Capacitor
Optimal Node	–	61	64	62
Size of Capacitor (kVAr)	–	1330	1147	1306
Active Power Loss (kW)	224.9219	151.9914	159.9948	152.9063
Reactive Power Loss (kVAr)	102.1295	70.4804	74.5505	70.9602
Minimum Voltage (node)	0.9092 (65)	0.9307(65)	0.9308 (61)	0.9308 (65)
Minimum VSI (node)	0.6767 (65)	0.7434(65)	0.7474 (62)	0.7436 (65)

Fig. 4.6 shows the Voltage profile Vs Node number for the base case and after implementation of the capacitor at optimal nodes for 69 node RDN.

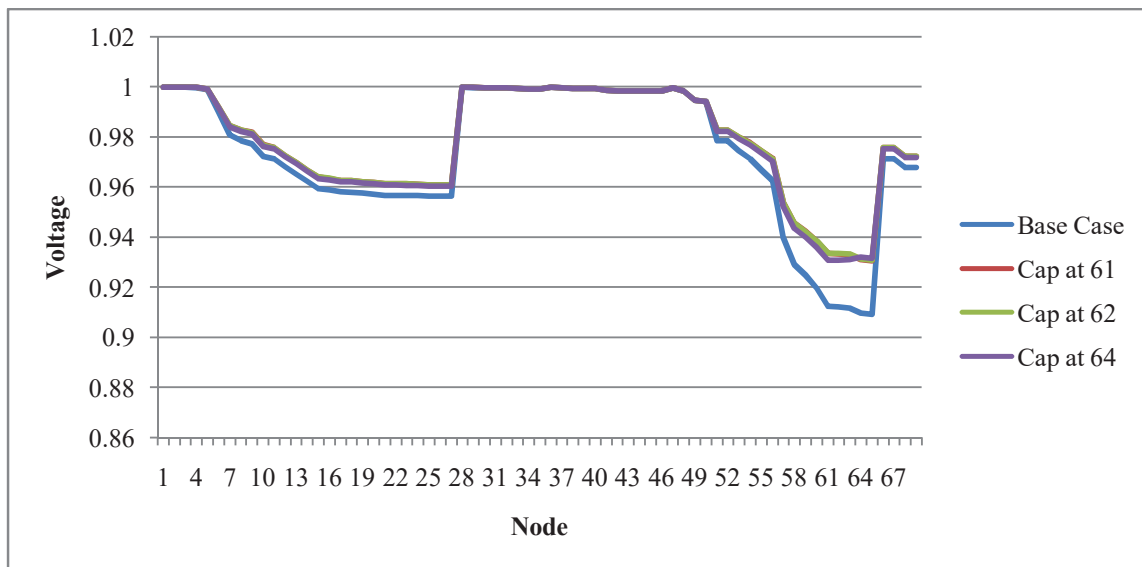


Fig. 4.6 Voltage Vs Node

Fig. 4.7 shows the VSI Vs Node number for the base case and after implementation of the capacitor at optimal nodes for 69 node RDN.

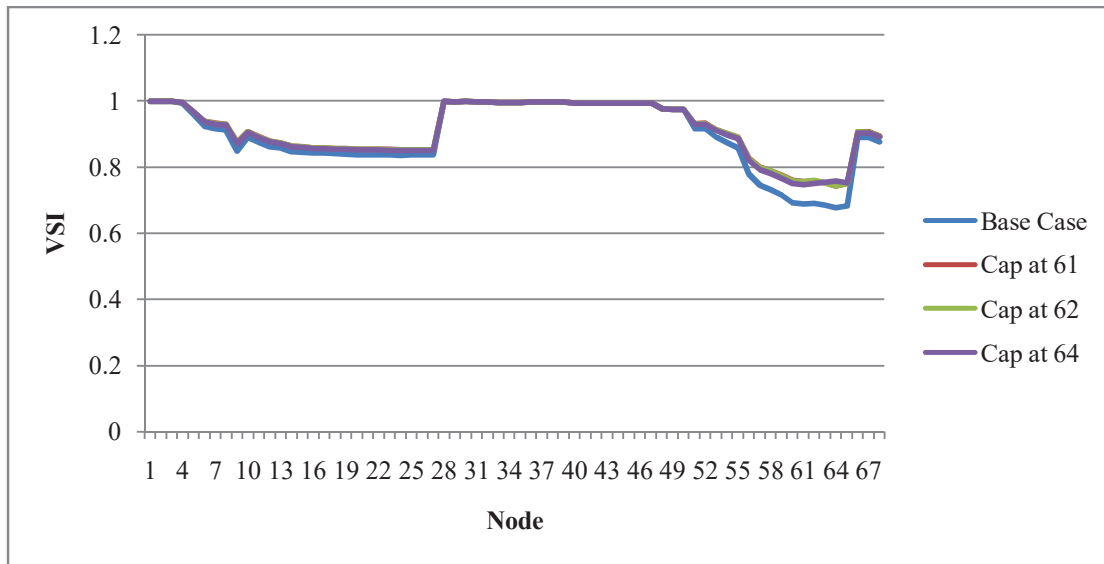


Fig. 4.7 VSI Vs Node

Fig. 4.8 shows the Power loss Vs Branch number for the base case and after implementation of the capacitor at optimal nodes for 69 node RDN.

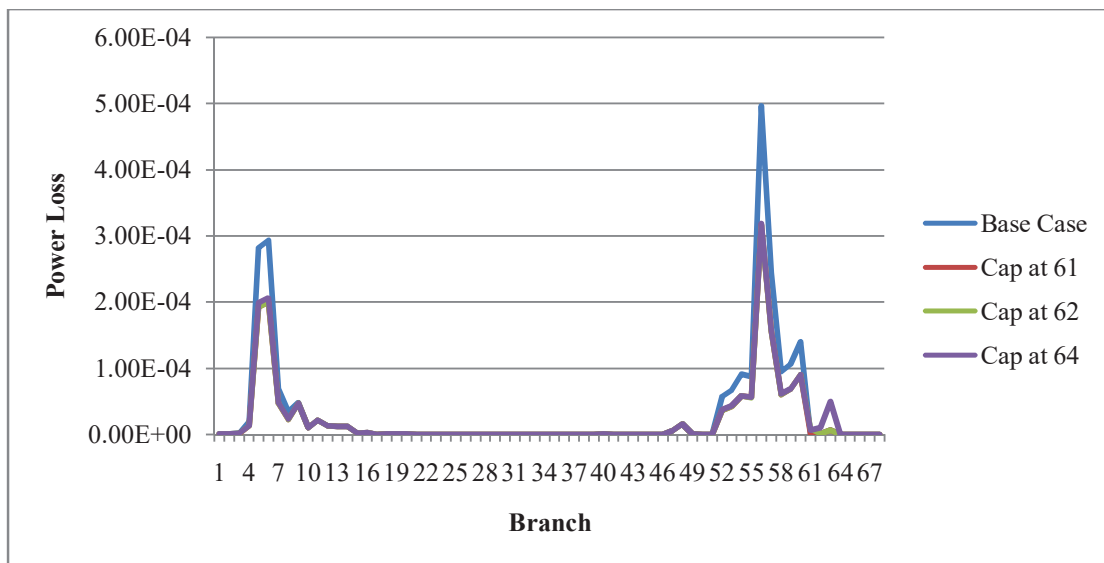


Fig 4.8 Power loss Vs Branch

4.1.3 Case-3 With DG and Capacitor at Same Node

Table 4.3: Performance analysis with DG and capacitor in 69 node RDN

Case-3	Base Case	With DG and Capacitor	With DG and Capacitor	With DG and Capacitor
Optimal Node	–	62 (D&C)	61(D &C)	64(D&C)
Size of DG and Capacitor	–	1848,1306	1872,1330	1650,1147
Active Power Loss (kW)	224.9219	25.1715	73.5892	40.7427
Reactive Power Loss (kVAr)	102.1295	15.3696	34.4718	23.5788
Minimum Voltage (node)	0.9092 (65)	0.9726 (27)	0.9761 (27)	0.9709 (27)
Minimum VSI (node)	0.6767 (65)	0.8947 (25)	0.9074 (25)	0.8882 (25)

Fig. 4.9 shows the Voltage profile Vs Node number for the base case and after implementation of DG and the capacitor at same optimal node for 69 node RDN.

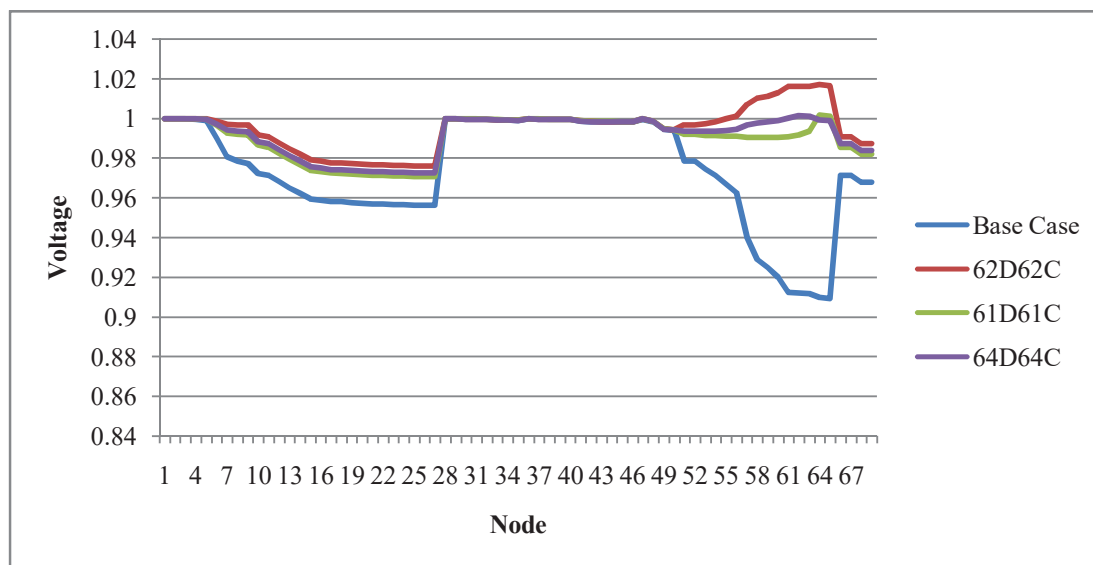


Fig. 4.9 Voltage Vs Node

Fig. 4.10 shows the VSI Vs Node number for the base case and after implementation of DG and the capacitor at same optimal nodes for 69 node RDN.

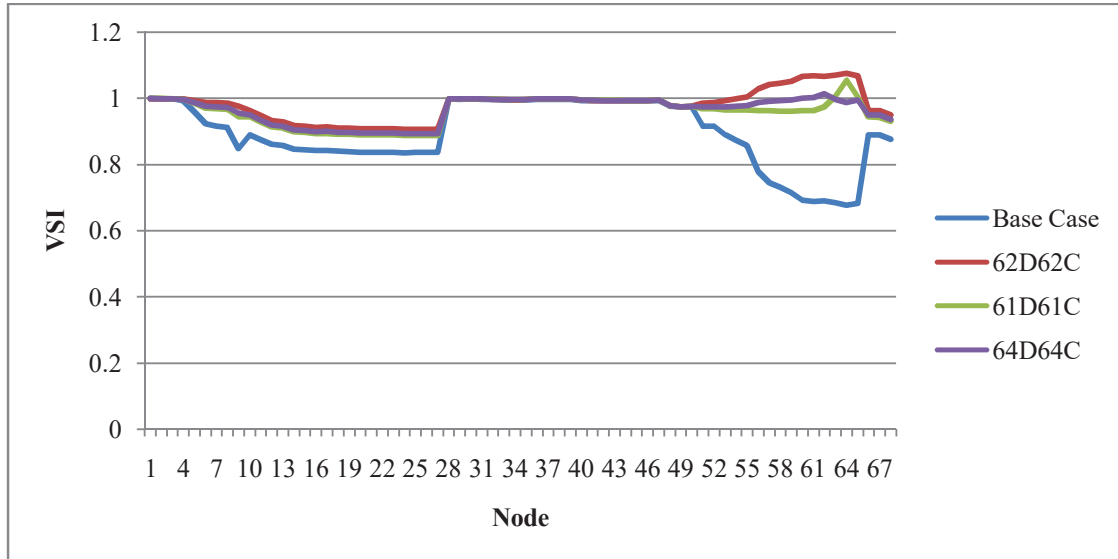


Fig. 4.10 VSI Vs Node

Fig. 4.11 shows the Power loss Vs Branch number for the base case and after implementation of DG and the capacitor at same optimal nodes for 69 node RDN.

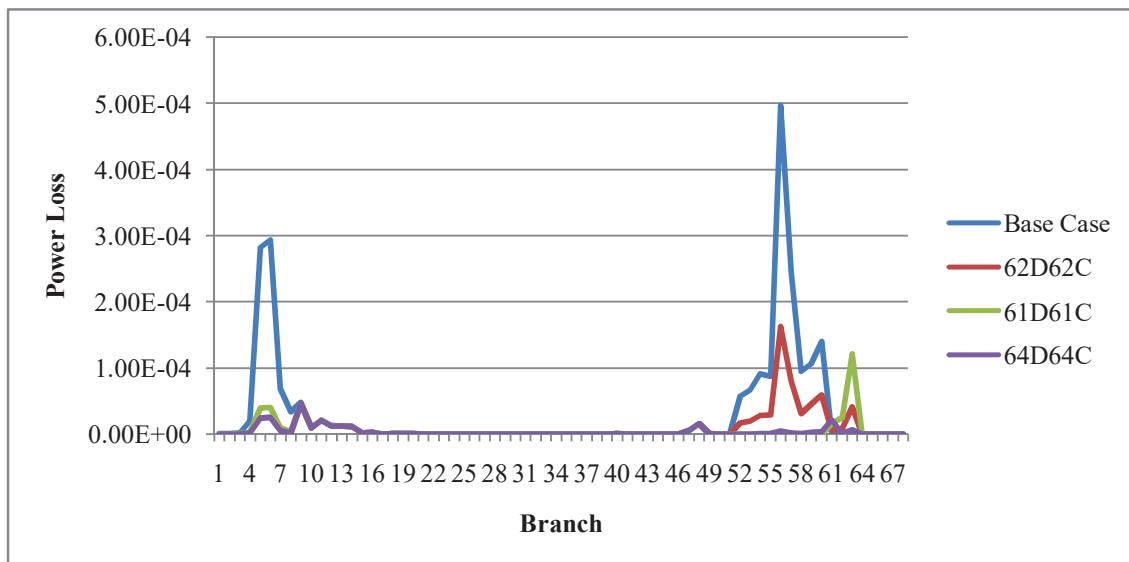


Fig. 4.11 Power loss Vs Branch

4.1.4 Case-4 Hybrid Arrangement

Table 4.4: Performance analysis with hybrid arrangement in 69 node RDN

Case-4	Base Case	With DG and Capacitor	With DG and Capacitor	With DG and Capacitor	With DG and Capacitor	With DG and Capacitor	With DG and Capacitor
Optimal Node	–	61(D), 64(C)	64(D), 61(C)	61(D), 62(C)	62(D), 61(C)	62(D), 64(C)	64(D), 62(C)
Size of DG and Capacitor	–	1872,1147	1650,1330	1872,1306	1848,1330	1848,1147	1650,1306
Active Power Loss (kW)	224.9219	29.0263	34.8456	23.8699	24.5269	30.3350	35.5052
Reactive Power Loss (kVAr)	102.1295	17.3829	20.4652	14.6637	15.0127	18.0913	20.8285
Minimum Voltage (node)	0.9092 (65)	0.9723 (27)	0.9715 (27)	0.9728 (27)	0.9727 (27)	0.9721 (27)	0.9714 (27)
Minimum VSI (node)	0.6767 (65)	0.8933 (25)	0.8904 (25)	0.8952 (25)	0.8949 (25)	0.8927 (25)	0.8901 (25)

Fig. 4.12 shows the Voltage profile Vs Node number for the base case and after implementation of DG and capacitor at different combinations of optimal nodes for 69 node RDN.

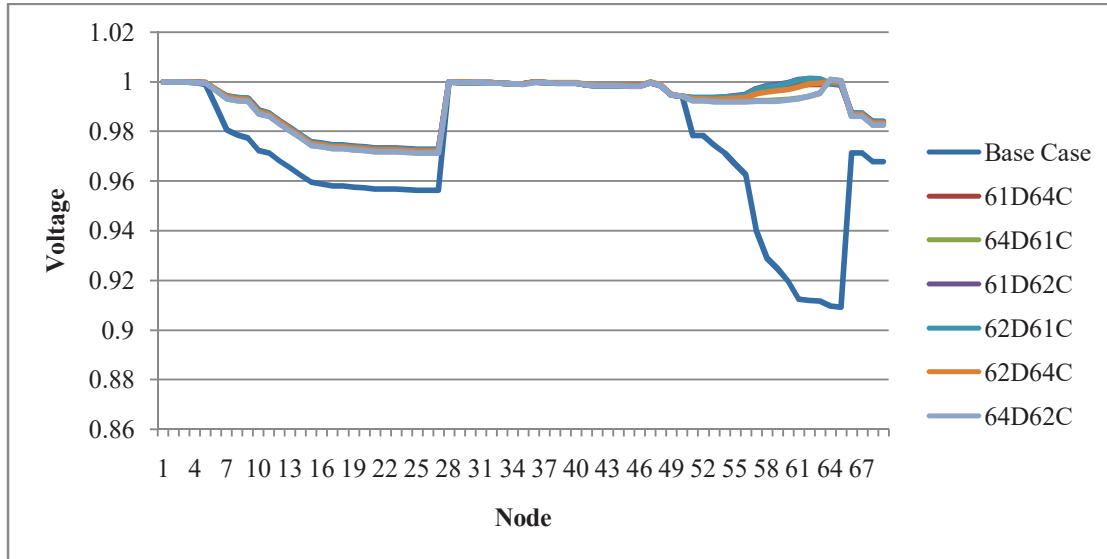


Fig. 4.12 Voltage Vs Node

Fig. 4.13 shows the VSI Vs Node number for the base case and after implementation of DG and capacitor at different combinations of optimal nodes for 69 node RDN.

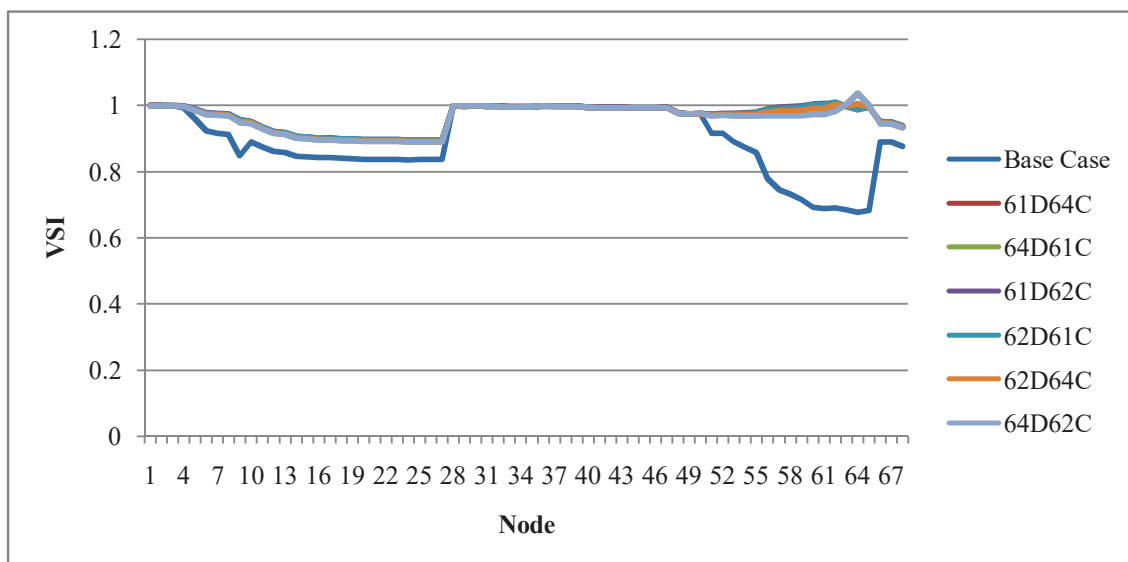


Fig. 4.13 VSI Vs Node

Fig. 4.14 shows the Power loss Vs Branch number for base case and after implementation of DG and capacitor at different combinations of optimal nodes for 69 node RDN.

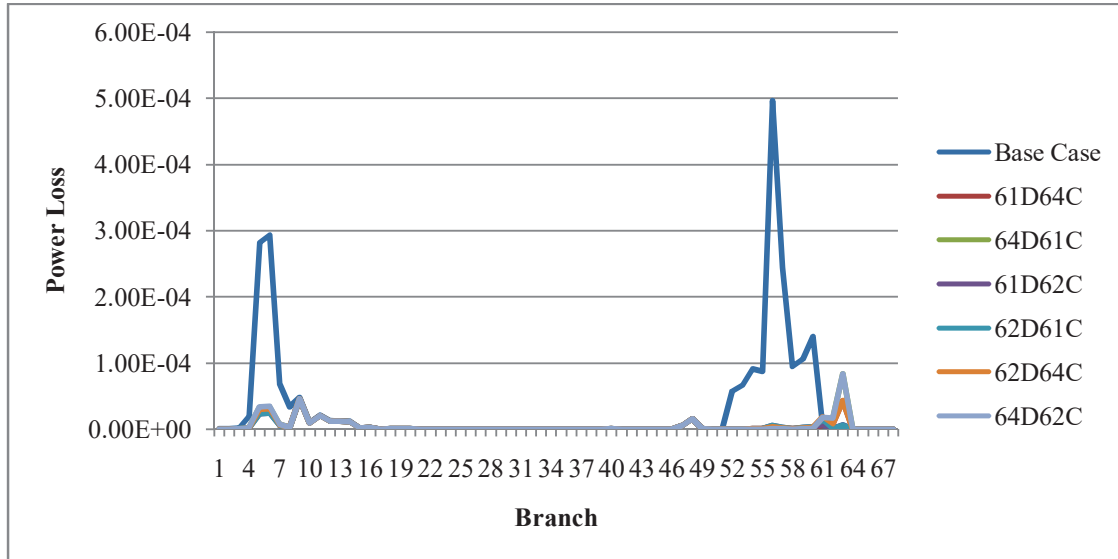


Fig. 4.14 Power loss Vs Branch

4.2 For 33 Node

4.2.1 Case-1 With DG

Table 4.5: Performance analysis with DG in 33 node RDN

Case-1	Base Case	With DG	With DG	With DG
Optimal Node	–	6	18	33
Size of DG (kW)	–	2580	850	1225
Active Power Loss (kW)	202.6662	103.9652	144.2276	129.6532
Reactive Power Loss (kVAr)	135.1477	74.8050	99.3170	93.3986
Minimum Voltage (node)	0.9131 (18)	0.9511(18)	0.9295 (33)	0.9316 (18)
Minimum VSI (node)	0.6931 (31)	0.8161 (31)	0.7334 (31)	0.7519 (18)

Fig. 4.15 shows the Voltage profile Vs Node number for base case and after implementation of DG at optimal nodes for 33 node RDN.

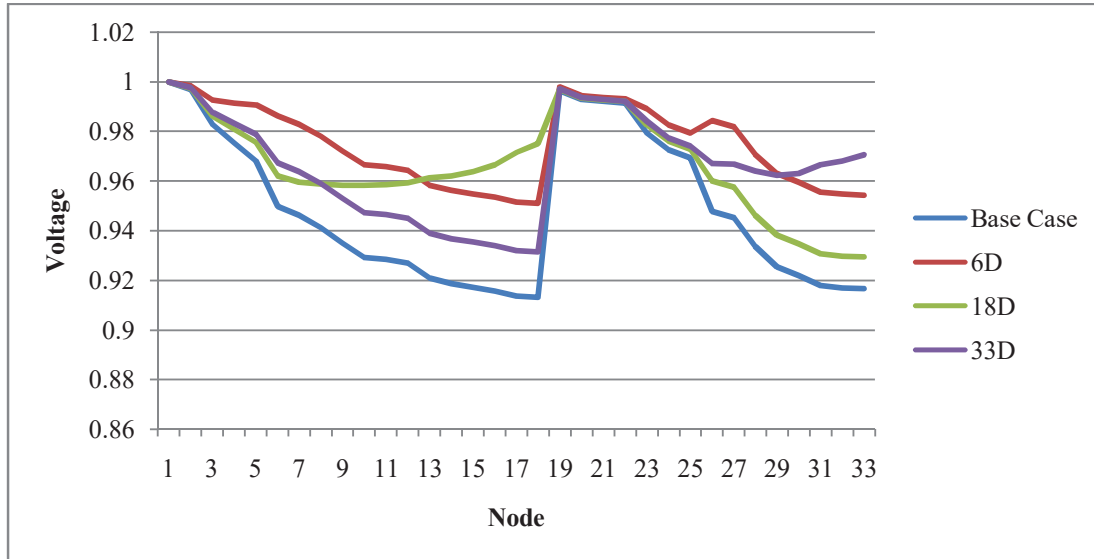


Fig. 4.15 Voltage Vs Node

Fig. 4.16 shows the VSI Vs Node number for the base case and after implementation of DG at optimal nodes for 33 node RDN.

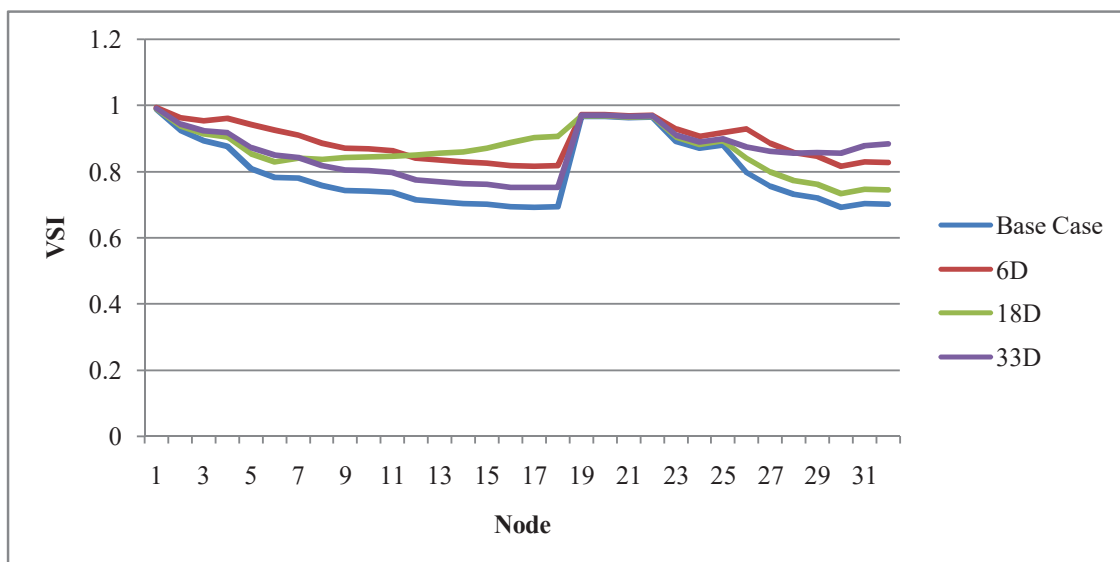


Fig 4.16 VSI Vs Node

Fig. 4.17 shows the Power loss Vs Branch number for the base case and after implementation of DG at optimal nodes for 33 node RDN.

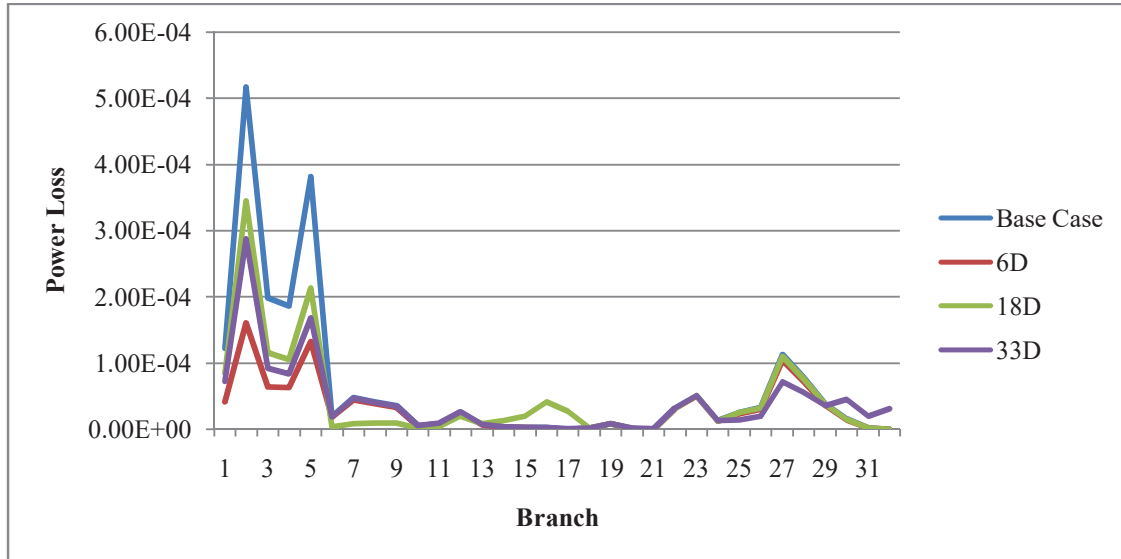


Fig. 4.17 Power loss Vs Branch

4.2.2 Case-2 With Capacitor

Table 4.6: Performance analysis with capacitor in 33 node RDN

Case-2	Base Case	With Capacitor	With Capacitor	With Capacitor
Optimal Node	–	6	18	33
Size of Capacitor (kVAr)	–	1791	486	981
Active Power Loss (kW)	202.6662	154.4160	182.5141	154.4139
Reactive Power Loss (kVAr)	135.1477	105.1764	123.4464	106.8409
Minimum Voltage (node)	0.9131 (18)	0.9303 (18)	0.9213 (33)	0.9229 (18)
Minimum VSI (node)	0.6931 (31)	0.7470 (31)	0.7076 (31)	0.7242 (18)

Fig. 4.18 shows the Voltage profile Vs Node number for the base case and after implementation of the capacitor at optimal nodes for 33 node RDN.

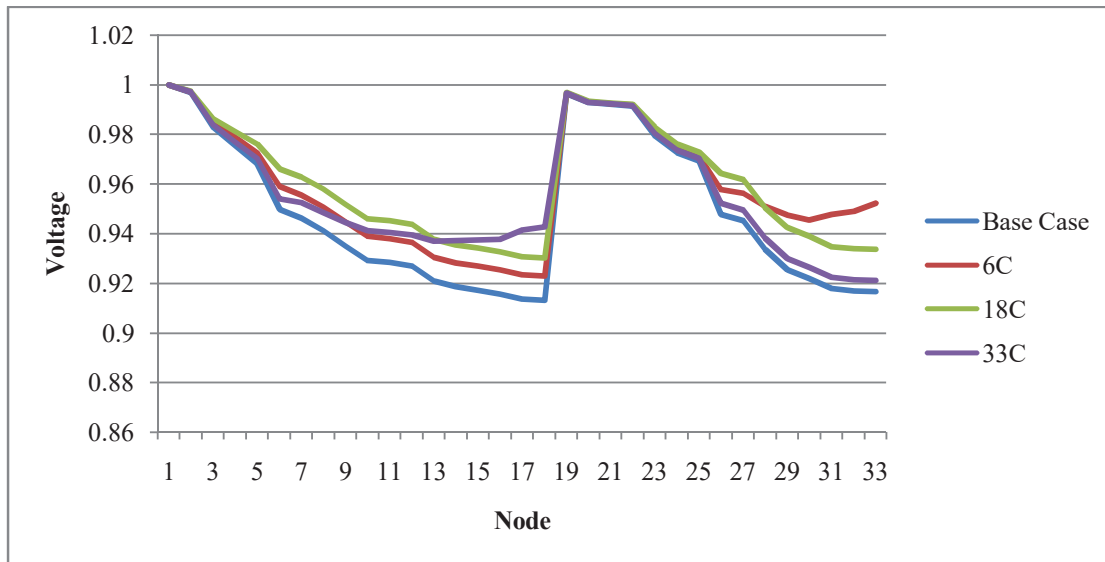


Fig. 4.18 Voltage Vs Node

Fig. 4.19 shows the VSI Vs Node number for the base case and after implementation of the capacitor at optimal nodes for 33 node RDN.

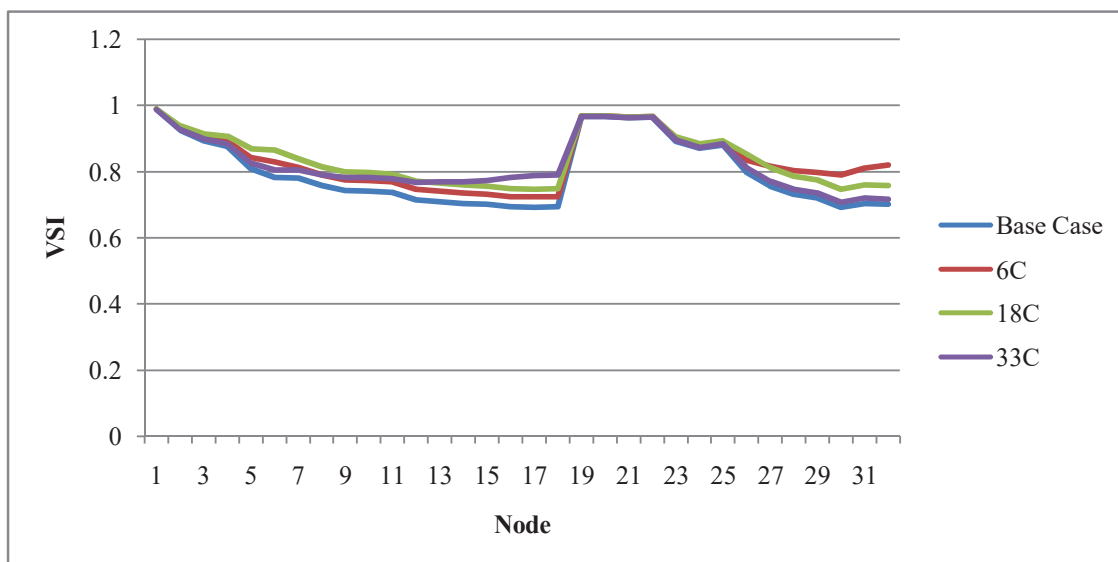


Fig. 4.19 VSI Vs Node

Fig. 4.20 shows the Power loss Vs Branch number for the base case and after implementation of the capacitor at optimal nodes for 33 node RDN.

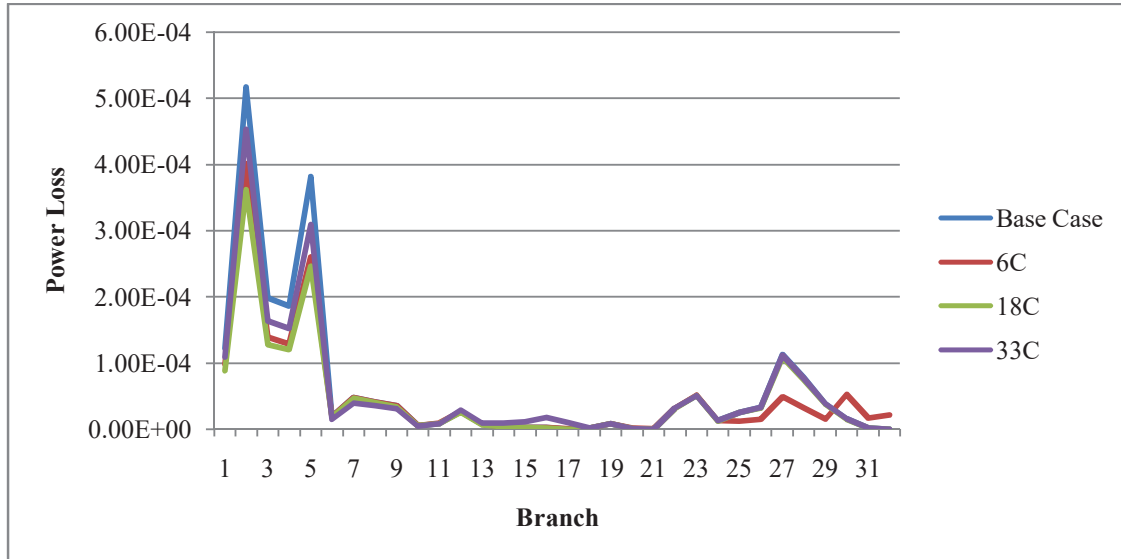


Fig. 4.20 Power loss Vs Branch

4.2.3 Case-3 DG and Capacitor at Same Node

Table 4.7: Performance analysis with DG and capacitor in 33 node RDN

Case-3	Base Case	With DG and Capacitor	With DG and Capacitor	With DG and Capacitor
Optimal Node	–	6 (D & C)	18 (D & C)	33 (D & C)
Size of DG and Capacitor	–	2580,1791	850,486	1225,981
Active Power Loss (kW)	202.6662	61.3961	123.7029	83.8176
Reactive Power Loss (kVAr)	135.1477	48.4651	86.9786	66.0318
Minimum Voltage (node)	0.9131 (18)	0.9676 (18)	0.9342 (33)	0.9411 (18)
Minimum VSI (node)	0.6931 (31)	0.8744 (31)	0.7484 (31)	0.7833 (18)

Fig. 4.21 shows the Voltage profile Vs Node number for the base case and after implementation of DG and the capacitor at same optimal nodes for 33 node RDN.

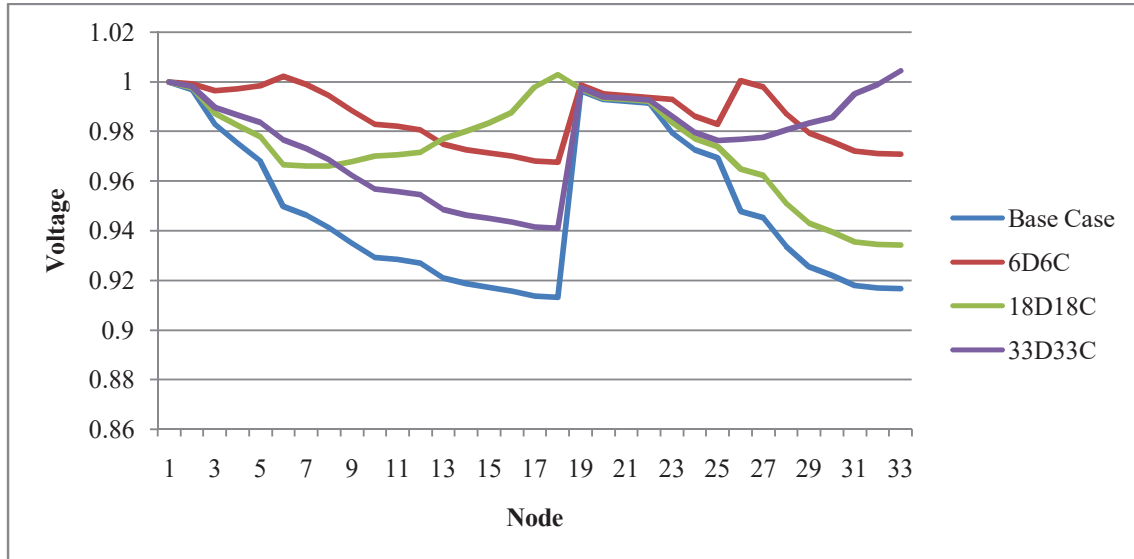


Fig. 4.21 Voltage Vs Node

Fig. 4.22 shows the VSI Vs Node number for the base case and after implementation of DG and the capacitor at same optimal nodes for 33 node RDN.

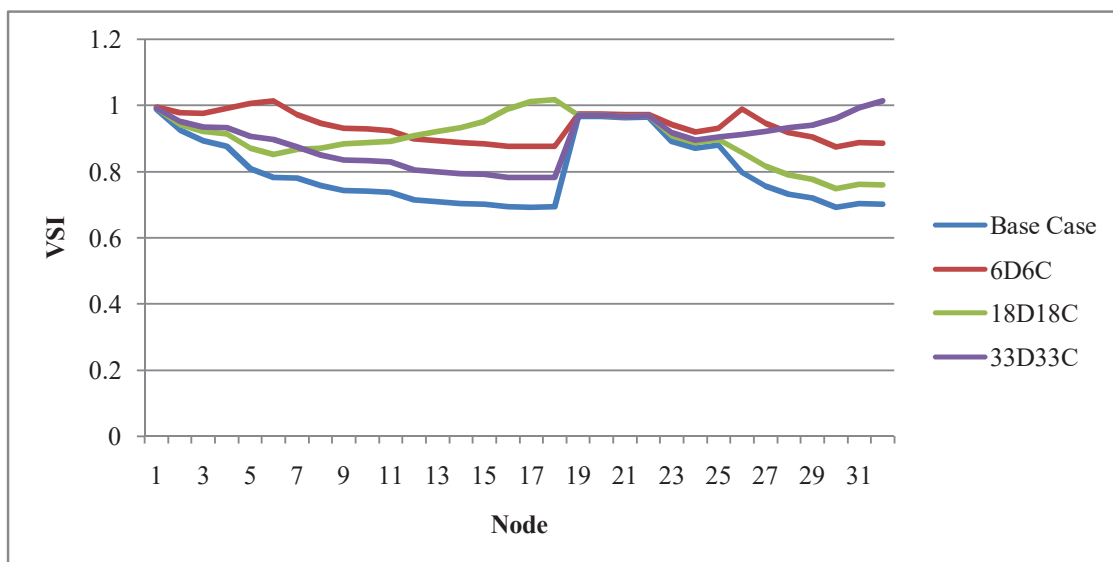


Fig. 4.22 VSI Vs Node

Fig. 4.23 shows the Power loss Vs Branch number for the base case and after implementation of DG and the capacitor at same optimal nodes for 33 node RDN.

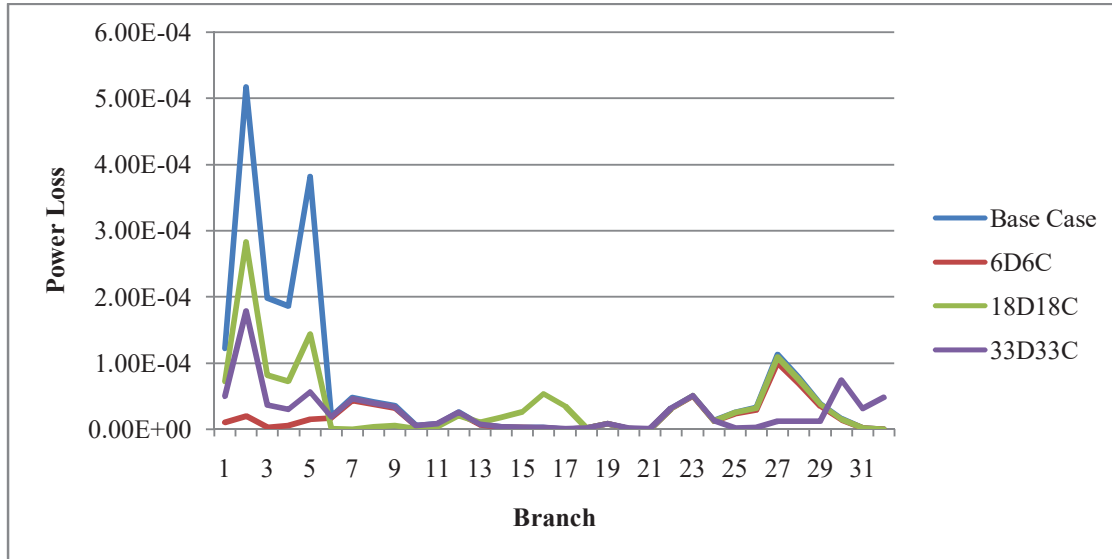


Fig. 4.23 Power loss Vs Branch

4.2.4 Case-4 Hybrid Arrangement

Table 4.8: Performance analysis with hybrid arrangement in 33 node RDN

Case-4	Base Case	With DG and Capacitor	With DG and Capacitor	With DG and Capacitor	With DG and Capacitor	With DG and Capacitor	With DG and Capacitor
Optimal Node	–	6(D), 18(C)	18(D), 6(C)	33(D), 6(C)	6(D), 33(C)	18(D), 33(C)	33(D), 18(C)
Size of DG and Capacitor	–	2580,486	850,1791	1225,1791	2580,981	850, 981	1225,486
Active Power Loss (kW)	202.6662	85.7532	98.9329	84.9691	61.1830	98.4646	110.6731
Reactive Power Loss (kVAr)	135.1477	64.2769	71.2248	65.5961	49.8564	72.5472	82.3820
Minimum Voltage (node)	0.9131 (18)	0.9590 (33)	0.9465 (33)	0.9485 (18)	0.9605 (18)	0.9581 (30)	0.9552 (13)
Minimum VSI (node)	0.6931 (31)	0.8319 (31)	0.7888 (31)	0.8080 (18)	0.8497 (18)	0.8321 (31)	0.8295 (13)

Fig. 4.24 shows the Voltage profile Vs Node number for the base case and after implementation of DG and capacitor at different combinations of optimal nodes for 33 node RDN.

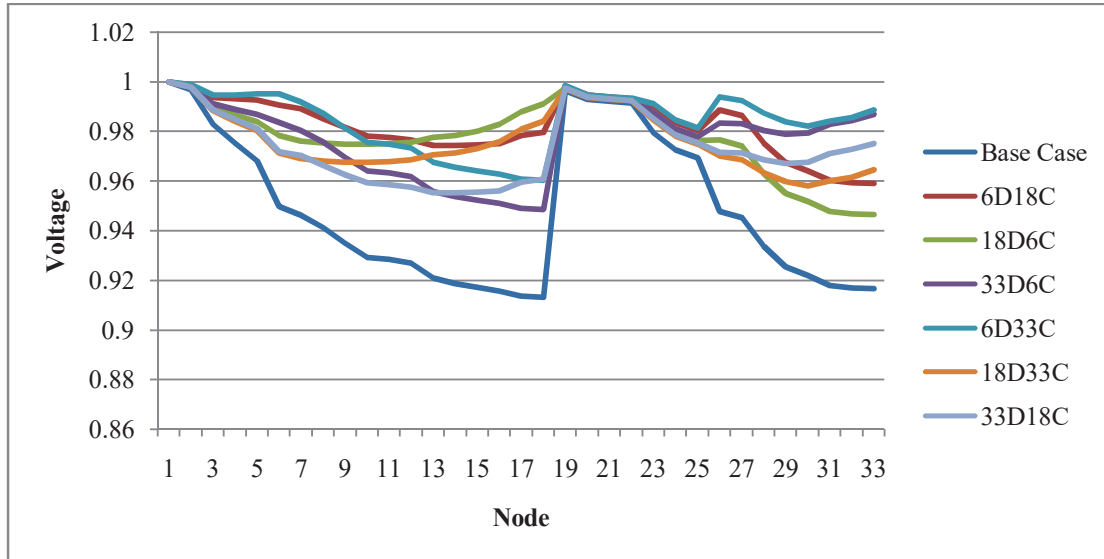


Fig. 4.24 Voltage Vs Node

Fig. 4.25 shows the VSI Vs Node number for base case and after implementation of DG and capacitor at different combinations of optimal nodes for 33 node RDN.

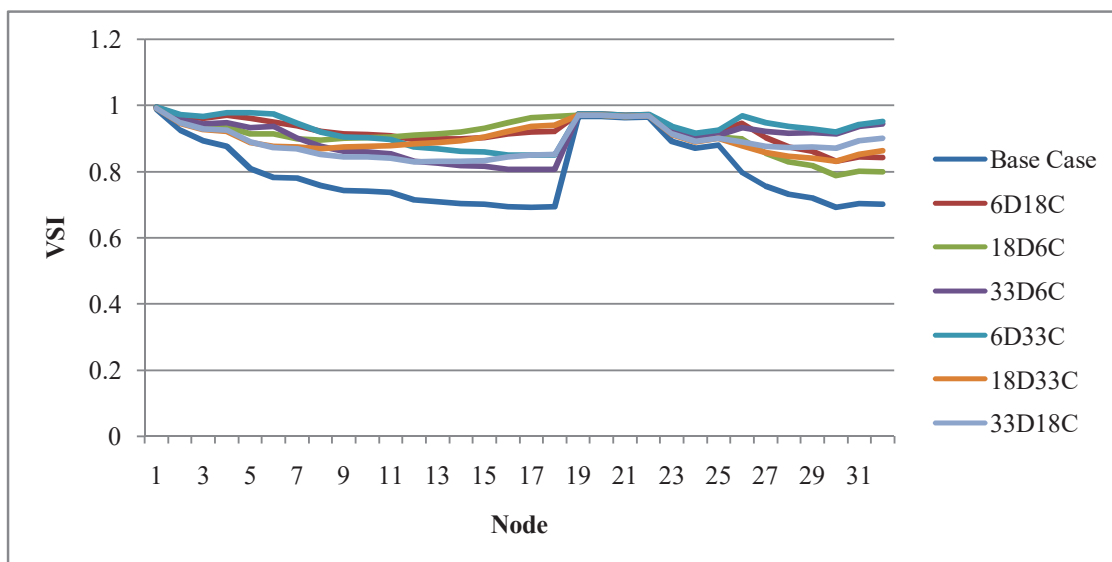


Fig. 4.25 VSI Vs Node

Fig. 4.26 shows the Power loss Vs Branch number for base case and after implementation of DG and capacitor at different combinations of optimal nodes for 33 node RDN.

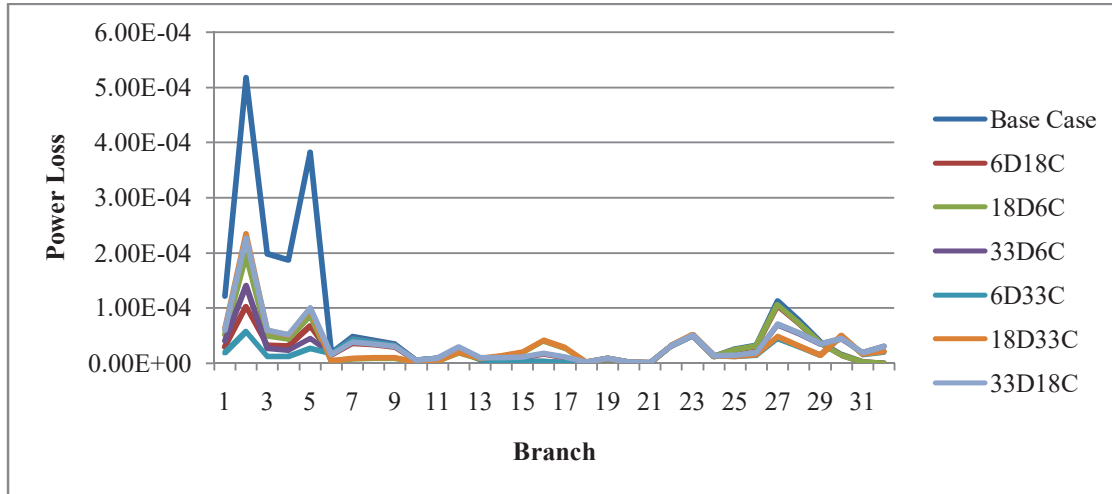


Fig. 4.26 Power loss Vs Branch

CHAPTER 5

CONCLUSIONS AND FUTURE SCOPE

Conclusions

In this thesis, the best location and size of DG and the capacitor is identified with the help of analytical method for 33 node and 69 node RDNs to minimize the loss reduction and improve the margin of voltage stability of the system. The results are obtained for the base case as well as after implementing the DG, Capacitor and DG plus capacitor for both the systems. After implementing the dispersed generator, capacitor and DG plus capacitor the loss in each node is significantly reduced and the voltage profile of the system has been improved. Hence VSI has also been improved in each case compared to base case. The combined placement of DG and capacitor has given the best result compared to DG placement or capacitor placement.

Future Scope

The following works can be done:-

- 1) DG and capacitor placement in Fuzzy domain.
- 2) The size can be optimized using hybrid algorithm.

LIST OF PUBLICATIONS

- 1) Kumar Pratik , and Suman Bhullar. “Literature Survey on Voltage Stability Improvement of Radial Distribution Networks”,Communicated to International Journal of Scientific Research and Education.

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APPENDIX-A

A.1 System data of 33 node RDN [1]

Line Number	Branch		Branch impedance		Loads	
	Sending End	Receiving End	Resistance (Ω)	Reactance (Ω)	P (kW)	Q (kVAr)
1	1	2	0.0922	0.047	100	60
2	2	3	0.493	0.2511	90	40
3	3	4	0.366	0.1864	120	80
4	4	5	0.381	0.1941	60	30
5	5	6	0.819	0.707	60	20
6	6	7	0.187	0.6188	200	100
7	7	8	0.711	0.2351	200	100
8	8	9	1.030	0.74	60	20
9	9	10	1.044	0.74	60	20
10	10	11	0.196	0.065	45	30
11	11	12	0.374	0.1298	60	35
12	12	13	1.468	1.155	60	35
13	13	14	0.5416	0.712	120	80
14	14	15	0.591	0.526	60	10
15	15	16	0.746	0.545	60	20
16	16	17	1.289	1.721	60	20
17	17	18	0.732	0.574	90	40
18	2	19	0.164	0.1565	90	40
19	19	20	1.504	1.3554	90	40
20	20	21	0.409	0.4784	90	40
21	21	22	0.708	0.9373	90	40
22	3	23	0.4512	0.3083	90	50
23	23	24	0.898	0.7091	420	200
24	24	25	0.896	0.7011	420	200
25	6	26	0.203	0.1034	60	25

26	26	27	0.284	0.1447	60	25
27	27	28	1.059	0.9337	60	20
28	28	29	0.804	0.7006	120	70
29	29	30	0.507	0.2585	200	600
30	30	31	0.974	0.963	150	70
31	31	32	0.310	0.3619	210	100
32	32	33	0.341	0.5302	60	40

Table A.2 System data of 69 node RDN [31]

Line Number	Branch		Branch impedance		Loads	
	Sending End	Receiving End	Resistance (Ω)	Reactance (Ω)	P (kW)	Q (kVAr)
1	1	2	0.036	0.01296	133.84	101.14
2	2	3	0.0005	0.0012	0	0
3	3	4	0.0015	0.0036	0	0
4	4	5	0.0251	0.0294	0	0
5	5	6	0.366	0.1864	2.6	2.2
6	6	7	0.3811	0.1941	40.4	30
7	7	8	0.0922	0.047	75	54
8	8	9	0.0493	0.0251	30	22
9	9	10	0.819	0.2707	28	19
10	10	11	0.1872	0.0619	145	104
11	11	12	0.7114	0.2351	145	104
12	12	13	1.03	0.34	8	5
13	13	14	1.044	0.345	8	5.5
14	14	15	1.058	0.3496	0	0
15	15	16	0.1966	0.065	45.5	30
16	16	17	0.3744	0.1238	60	35
17	17	18	0.0047	0.0016	60	35
18	18	19	0.3276	0.1083	0	0

19	19	20	0.2106	0.069	1	0.6
20	20	21	0.3416	0.1129	114	81
21	21	22	0.014	0.0046	5	3.5
22	22	23	0.1591	0.0526	0	0
23	23	24	0.3463	0.1145	28	20
24	24	25	0.7488	0.2475	0	0
25	25	26	0.3089	0.1021	14	10
26	26	27	0.1732	0.0572	14	10
27	3	28	0.0044	0.0108	26	18.6
28	28	29	0.064	0.1565	26	18.6
29	29	30	0.3978	0.1315	0	0
30	30	31	0.0702	0.0232	0	0
31	31	32	0.351	0.116	0	0
32	32	33	0.839	0.2816	14	10
33	33	34	1.708	0.5646	9.5	14
34	34	35	1.474	0.4873	6	4
35	3	36	0.0044	0.0108	26	18.55
36	36	37	0.064	0.1565	26	18.55
37	37	38	0.1053	0.123	0	0
38	38	39	0.0304	0.0355	24	17
39	39	40	0.0018	0.0021	24	17
40	40	41	0.7283	0.8509	1.2	1
41	41	42	0.31	0.3623	0	0
42	42	43	0.041	0.0478	6	4.3
43	43	44	0.0092	0.0116	0	0
44	44	45	0.1089	0.1373	39.22	26.3
45	45	46	0.0009	0.0012	39.22	26.3
46	4	47	0.0034	0.0084	0	0
47	47	48	0.0851	0.2083	79	56.4
48	48	49	0.2898	0.7091	384.7	274.5
49	49	50	0.0822	0.2011	384.7	274.5

50	8	51	0.0928	0.0473	40.5	28.3
51	51	52	0.3319	0.1114	3.6	2.7
52	9	53	0.174	0.0886	4.35	3.5
53	53	54	0.203	0.1034	26.4	19
54	54	55	0.2842	0.1447	24	17.2
55	55	56	0.2813	0.1433	0	0
56	56	57	1.59	0.5337	0	0
57	57	58	0.7837	0.263	0	0
58	58	59	0.3042	0.1006	100	72
59	59	60	0.3861	0.1172	0	0
60	60	61	0.5075	0.2585	1244	888
61	61	62	0.0974	0.0496	32	23
62	62	63	0.145	0.0738	0	0
63	63	64	0.7105	0.3619	227	162
64	64	65	1.041	0.5302	59	42
65	11	66	0.2012	0.0611	18	13
66	66	67	0.0047	0.0014	18	13
67	12	68	0.7394	0.2444	28	20
68	68	69	0.0047	0.0016	28	20

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