Planning and Operation of DSTATCOM in Electrical Distribution Systems

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Planning and Operation of DSTATCOM in Electrical Distribution Systems

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in

Electrical Engineering

by

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I, *Joseph Sanam*, Roll Number 513EE1016 hereby declare that this dissertation entitled *“Planning and Operation of DSTATCOM in Electrical Distribution Systems”* represents my original work carried out as a doctoral student of NIT Rourkela and, to the best of my knowledge, it contains no material previously published or written by another person, nor any material presented for the award of any other degree or diploma of NIT Rourkela or any other institution. Any contribution made to this research by others, with whom I have worked at NIT Rourkela or elsewhere, is explicitly acknowledged in the dissertation. The works of other authors cited in this dissertation have been duly acknowledged under the section "Bibliography". I have also submitted my original research records to the doctoral scrutiny committee for evaluation of my dissertation.

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List of Abbreviations

S. No	Acronym	Abbreviation
1	DSTATCOM	Distribution Static Synchronous Compensator
2	DEA	Differential Evolution Algorithm
3	ELC	Energy loss cost
4	PWF	Present worth factor
5	DN	Distribution networks
6	DISCO	Distribution companies
7	DG	Distribution generators
8	NPV	Net present value
9	PV	Photovoltaic
10	ACO	Ant colony optimization
11	O&M	Operating and maintenance
12	FBS	Forward-Backward sweep
13	VSC	Voltage source converter
14	PCC	Point of common coupling
15	TNP	Total net profit
16	PH	Planning horizon
17	RDN	Radial distribution network
18	DG	Distributed generation
19	ESM	Exhaustive search method
20	AVR	Automatic voltage regulator
21	DFACTS	Distribution network flexible AC transmission

22	UPQC	Unified power flow conditioner
23	SSSC	Static synchronous series compensator
24	RDS	Radial distribution systems
25	DVR	Dynamic voltage restorer
26	NP	Number of population
27	D	String dimension
28	CR	Crossover rate
29	F	Scaling factor
30	TPC	Total planning cost
31	PV	Photovoltaic
32	ACO	Ant colony otimization
33	O&M	Operational and maintenance
34	kVAr	Kilo volt ampere
35	kW	Kilo watt
36	IA	Immune algorithm
37	CPU	Central processing unit
38	PSO	Particle swarm optimization
39	TG	Target vector
40	MUT	Mutant vector

Notations

S. No	Notation	Description
1	P_{Gi}	Real power generated
2	Q_{Gi}	Reactive power generated
3	P_{Li}	Real power load
4	Q_{Li}	Reactive power load
5	$\lvert V_i \rvert$	Voltage magnitude at bus i
6	$n, n+1$	Node numbers
7	R_n+jX_n	Line impedance,
8	P_n, Q_n	Real and reactive power demand at the n^{th} node
9	V_n	Voltage in n^{th} node
10	α_n	Angle of V_n
11	β_{n+1}	Angle of V_{n+1}
12	I_n	Current flowing from n^{th} to $n+1^{\text{th}}$ node
13	δ	Angle of I_n
14	I_{DSTAT}	DSTATCOM current
15	V'_n	Voltage in n^{th} node after the placement of DSTATCOM
16	α_n'	Angle of V'_n after the placement of DSTATCOM
17	β'_{n+1}	Angle of V'_{n+1} after the placement of DSTATCOM
18	P_{loss}	Active power loss
19	Q_{loss}	Reactive power loss
20	I_j^{max}	Maximum limit of the current in the branch j.
21	$P^{i,i+1}{}_{loss}$	Active power loss between two buses i, i+1
22	$Q^{i,i+1}{}_{loss}$	Reactive power loss between two buses i, i+1

23	$R^{i,i+1}{}_{loss}$	Resistance between two buses *i, i*+1
24	I_{line}	Line current
25	I_{load}	Load current
26	$X^{i,i+1}{}_{loss}$	Reactance between two buses *i, i*+1
27	C_e	Energy cost per kWh
28	f_{21}	Total initial capital investment cost the DSTATCOM
29	f_{22}	Total operational cost of the DSTATCOM
30	f_{23}	Total maintenance costs of the DSTATCOM
31	T_k	Duration of time in k^{th} load level
32	C_{in}	Initial capital investment cost of DSTATCOM per kVAr
33	C_{op}	Operational cost of the DSTATCOM per kWh
34	C_{ma}	DSTATCOM maintenance cost which in terms of the % of initial cost
35	Q_k^{DSTAT}	Size of the DSTATCOM placed at optimal location during k^{th} load level
36	k_{ck}	Proportionality constant of k^{th} load level
37	$P_{loss_k}^{DSTAT}$	Active power loss during k^{th} load level after DSTATCOM is installed
38	k	Load level
39	$I_b(j)$	Line current of j^{th} branch
40	$R_b(j)$	Resistance of j^{th} branch
41	V_i^{min}	Minimum limits of the voltage at bus number *i*
42	V_i^{max}	Maximum limits of the voltage at bus number *i*

Abstract

In present day scenario, it is most essential to consider the maximum asset performance of the power distribution systems to reach the major goals to meet customer demands. To reach the goals, the planning optimization becomes crucial, aiming at the right level of reliability, maintaining the system at a low total cost while keeping good power quality. There are some problems encountered which are hindering the effective and efficient performance of the distribution systems to maintain power quality. These problems are higher power losses, poor voltage profile near to the end customers, harmonics in load currents, sags and swells in source voltage etc. All these problems may arise due to the presence of nonlinear loads, unpredictable loads, pulse loads, sensor and other energy loads, propulsion loads and DG connections etc. Hence, in order to improve the power quality of power distribution systems, it is required to set up some power quality mitigating devices, for example, distribution static synchronous compensator (DSTATCOM), dynamic voltage restorer (DVR), and unified power quality conditioner (UPQC) etc. The goal of this project work is to devise a planning of optimal allocation of DSTATCOM in distribution systems using optimization techniques so as to provide reactive power compensation and improve the power quality.

Keywords*: Distribution Systems; Power Loss; Voltage Profile; Forward- Backward Load flow algorithm; Phase angle Model of DSTATCOM; Differential Evolution Algorithms, Total Planning Cost; Total Net Profit; Planning Horizon; Present Worth Factor etc.

Chapter 1

Introduction

1.1. Brief description of Electric Power System

An electric power system is a network of various electrical Components(equipment) installed for the generation, transmission, distribution and utilization of electrical power. Power system consists of alternators that are driven by prime movers, grid, substations, transformers, circuit breakers, bus bars, and other auxiliary devices, etc. that are used to transfer power from generating stations to load in most reliable, economical and efficient manner [1] and [2].

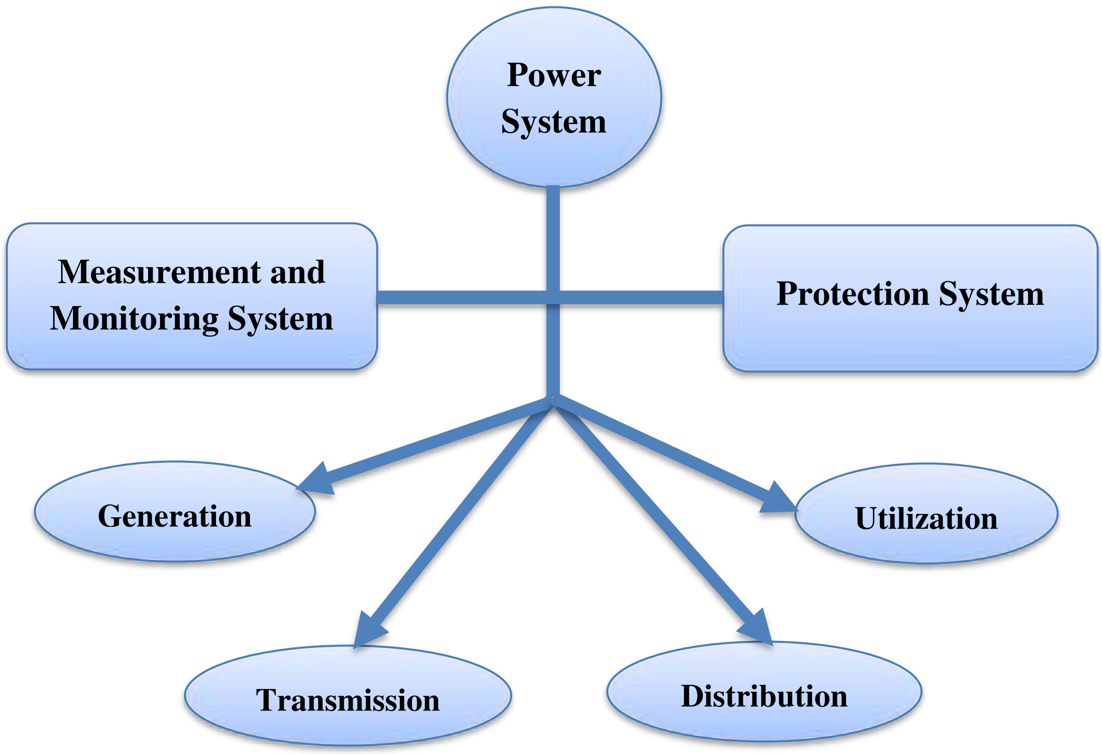

Figure.1.1: The block diagram of electric power system

Fig. 1.1 signifies the block diagram of electric power system. In the block diagram, it can be seen that the power system comprises the various stages of operations such as generation, transmission, distribution, and utilization along with the measurement of the monitoring system and protection system. The simple layout of the electric power system is shown in Fig. 1.2.

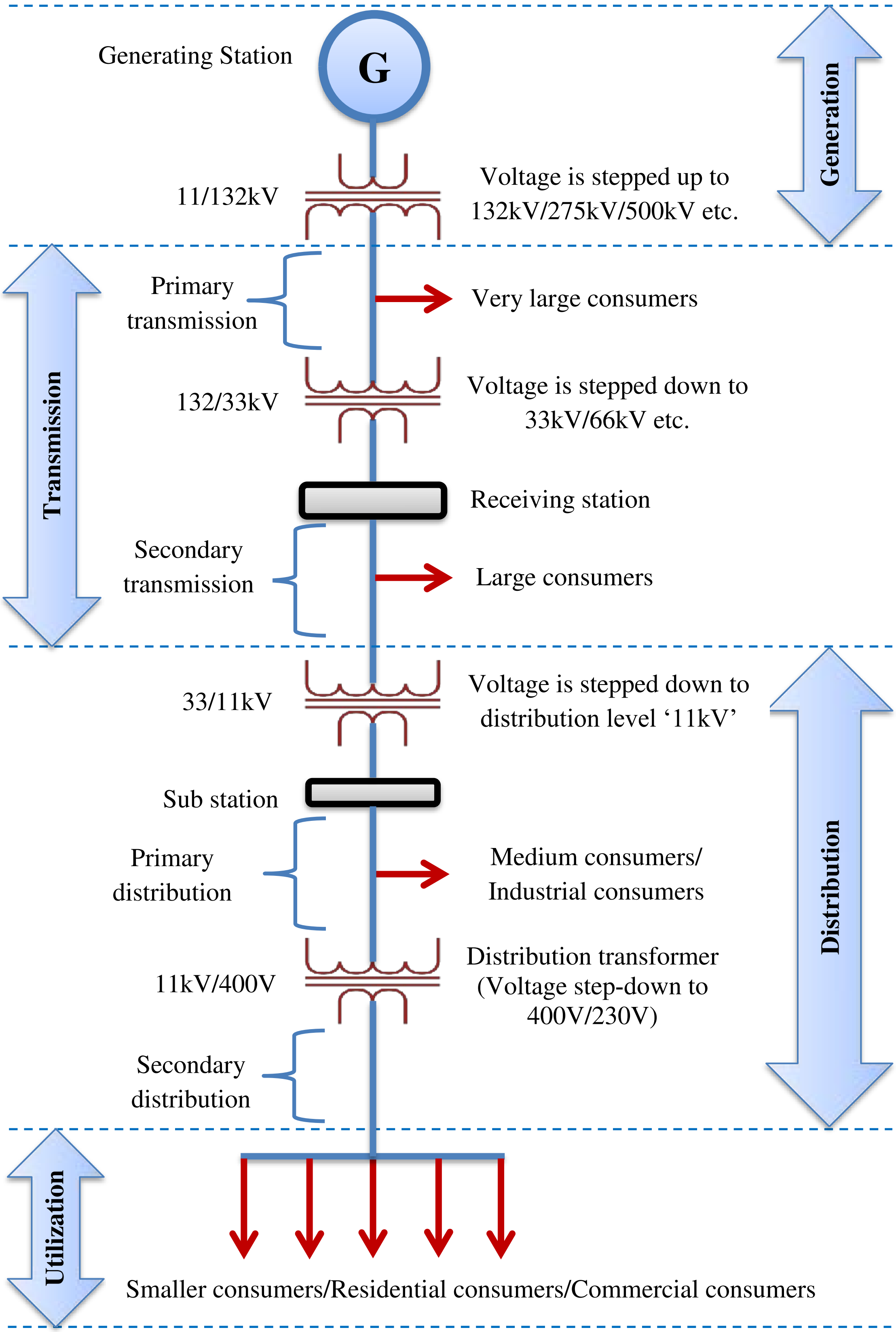

Figure.1.2: A simple layout of electric power system

In Fig.1.2, it is very clear that the power generated by generating stations flows through four stages to reach consumer's load such as generation, transmission, distribution and utilization. The transmission of power low has two steps i.e. primary and secondary transmission. Similarly, the distribution has two steps i.e. primary and secondary distribution. The power generating stations are usually located at a dam site where hydro energy is available, near a fuel source e.g. nuclear fuels such as uranium-235 or plutonium-239 and thermal energy fuels such as coal, natural gas, wood waste, etc., according to the availability of renewable energy sources such as solar, wind, rain, tides, waves, and geothermal heat etc. and in lightly populated areas [3] and [4].

The electric power which is generated by generating stations is at a low voltage around 11kV to 33kV depending on the output power rating of the generator. This voltage is stepped up to higher voltages such as 132kv or 275kV or 500kV etc. as shown in Fig. 1.2. The voltage which is stepped up is connected to the transmission system. The transmission system then will carry the electric power for long distances, now and then it flows through international boundaries too through two stages i.e. primary and secondary transmission, until it reaches the electric power distribution system. Very large loads are connected to the primary transmission system [5] and [6]. After the primary transmission, the voltage is stepped down to 132kV or 33kV and is connected to the receiving station where the large loads are being fed through the secondary transmission system [7]. At the end of secondary transmission, the power arrives the distribution system. In the distribution system, the voltage is stepped down to the voltage level of utilization through primary end secondary distribution system stages. The detailed discussion on distribution system is given in section 1.2.

1.1.1. Networks involved in electric power system

As it is discussed in above section, the power flow in electric power system happens through four stages to reach a consumer's load. These four stages are comprised with the combinatorial operation of various networks such as power grid, transmission network, substation network, and distribution network, etc.

I. **Power Grid:** The power grid is an interconnected system of several generating stations with the same relative frequency for delivering electricity from suppliers to consumers. The power grid can also be called as the combined operation of transmission and distribution systems. Power grid involves three things generating stations, transmission lines, and distribution lines [8].

II. **Transmission system**: The network/system which carries the bulk amount of electric power from generating stations to the distribution station and then to load station is called as the transmission system [9].

III. **Substation:** Substation is the part of the power system where the high transmission voltage is stepped down to lower distribution voltages suitable for the voltage levels required for industrial, commercial and residential consumers. The substation can also be called as the interconnection of two dissimilar transmission system voltages[10]. The substations are supervised and controlled using SCADA (supervisory control and data acquisition). When the electric power generated by the generating station flows to the consumer's load, it flows through various substations at different of voltages. Hence, the substations are classified as follows [11]:

a) Transmission Substation
b) Distribution Substation
c) Collector Substations
d) Converter Substation
e) Switching Substation
f) Traction Substation

a) Transmission Substation

The substation which connects two or more than two transmission lines at one point is nothing but transmission substation. This substation consists transformers to transform voltage from one transmission line to another, capacitors to improve the power factor, voltage controller to control the voltage at different frequencies, phase shifting transformers which control the power stream between two power systems that are adjacent to each other, and static VAR compensators. The large transmission substations are constructed with, several circuit breakers, multiple voltage levels and many numbers of control and protection and equipment (SCADA systems, relays, current and voltage transformers) to transmit the electric power to a large region in hectares [12].

b) Distribution Substation

The substation which transfers electric power from the transmission system to the distribution system of a region or zone is nothing but distribution substation. The voltages of this substation are medium voltage based on the size of the load area and the customs of indigenous utility. The more details of the distribution substations are given in section 1.2.

c) Collector Substation

The substation which is used in wind farm based distributed generations projects is called as collector substation. This substation collects power from several wind turbines and moves it to the transmission grid. The flow of power is in opposite direction though it resembles a distribution substation. The collector substation operates the voltage around 33kV or 35 kV only because of the economy of construction. This voltage gets stepped up to the level of grid voltage by the collector substation. These substations are also used in hydroelectric and thermal power plants whose output power almost same. This substation can correct the power factor and control the wind turbines etc [13].

d) Converter Substations

It's a substation which converts the power from A.C. to D.C. and vice versa using power electronic devices [14]. These substations are complex to operate but are required for transmitting HVDC (high voltage direct current) or interconnection of two A.C. networks or interconnection of non-synchronous networks. The main equipment includes the capacitors, filters, reactors and valves. The valves of the converter substations are located in the large transformers.

e) Switching Substation

The substation which operates the single voltage level without any transformer is known as switching substation. The switching substation can also be called as the switchyard and is connected to the power station directly or located just adjacent to the power station. The switch yard has two sides in which one side is the generator bus, and another side is the feeder bus. The power generated from the power station is supplied to the generator bus through one side of the switchyard, and the transmission lines take that power from the feeder bus through the other side of the switch yard. Hence, the switch yard connects and disconnects the transmission lines to and from the power station or other elements for switching the current to parallelizing circuits or backup lines in case of maintenance or failure, or new construction occurs, i.e., removing or adding transformers or transmission lines or some other elements. So, the switching substation causes the reliability of power supply [15].

f) Traction(railway) substation

Traction Substation is one which converts AC currents to DC currents to electrify DC trains and AC currents to AC currents at the different frequencies to electrify the AC trains. Hence the traction substations have the both the rectifier and inverter circuits. However, the output frequency of inverter circuit to electrify the AC trains is other than the that of the local(public) grid. If the railways operate their generators and grid, then the traction substation will also work as converter substation or transmission substation [16].

1.1.2. Planning, and operation of electric power systems

The planning, operation, and control of entire power systems are quite complex and crucial task since it is a large system which involves four stages of operation such as the generation, transmission, distribution, and utilization. There are two reasons why it is so complex, firstly, the entire system must be operated in synchronism. Secondly, the many various companies and organizations are involved in different portions of the entire system where they are needed to be more responsible. Hence, the optimal planning, operation, and control or power system are required to minimize the operational cost and delivering the secure and reliable power to the consumers. The whole operation of the power system is divided into three stages [17]-[20]:

a) Planning

b) Control

c) Accounting

a) Planning: The demand of the load varies in each hour, week, and month. As the load varies, the generation of the power varies to meet the anticipated demand. The generation fo the power depends on the availability of resources such as hydro energy (Water head), thermal energy fuels, nuclear energy fuels and renewable energy fuels. Hence, to meet the load demand in various periods of time, it is required to plan(schedule) the resources optimally. The optimal planning(scheduling) is nothing but the planning of resources, maintenance of equipment and the start-up and shutdown of generating units over many hours, weeks, and months [21].

b) Control: To respond the current demand of the load and some unexpected equipment outages the real time control of the power system is necessary. The real time control system helps to maintain the system security to avoid the disruptions in power supply due to unexpected equipment outages (contingency) [22].

c) Accounting: Accounting is nothing but "after-the-fact accounting" which tracks the sales and purchase of electrical energy among companies and organizations to generate the bills. These bills are useful to forecast the power demand and the corresponding requirement of generation fuels, also, to forecast the quality of power so that the shunt and series compensating devices can be added to the system to improve the power quality.

1.2. Overview of Electrical Distribution Systems

The electric power distribution system is the point where the power gets delivered from the transmission system to the costumer's Load (Utilization). The distribution system starts from the third stage of power systems as shown in Fig.1.2. On arrival of power at distribution systems from the secondary transmission, the voltage gets stepped down from the level of transmission to the level of distribution voltage (medium voltage) i.e. 33kV or 11kV using step-down transformers. This medium voltage is then transferred to the distribution transformers through the primary distribution system. Some consumer's loads such as medium loads or industrial loads that demand a large amount of power supply are directly connected to the primary distribution systems or the sub-transmission systems. After the primary distribution, the power enters into the distribution wiring through a substation and then finally arrives the service location where the power stopped down to the level of utilization at the voltage of 3.3kV or 400V or 230V which is called the secondary distribution. The secondary distribution system feeds smaller loads or commercial loads or residential loads [23]-[26].

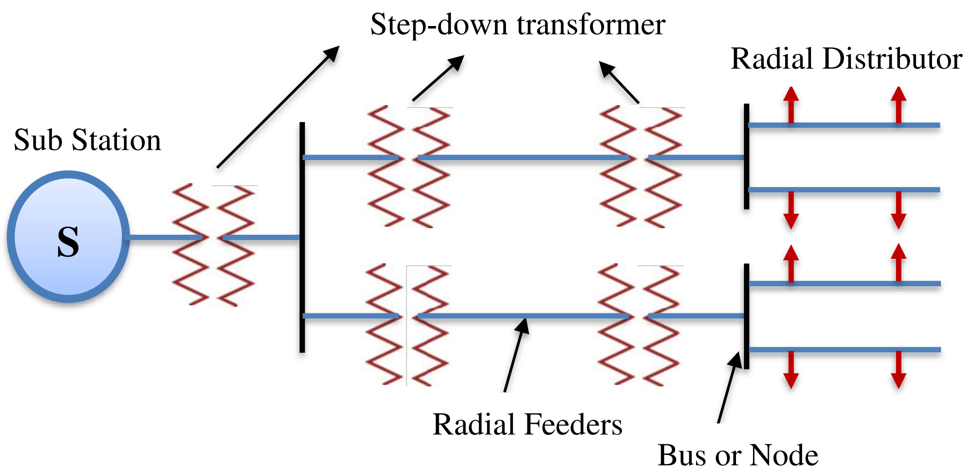

Figure.1.3: The line diagram of radial distribution system

It can be understood from Figs 1.2 and 1.3 that the distribution substation has at least two sub-transmission or transmission lines as input and the several feeders as output. The distribution feeders run along the roads underground or overhead lines and carry the power to the consumer's load through the distribution transformers. Many at times the distribution substations not only transforming the voltage but isolate faults in either distribution or transmission systems. A simple line diagram of the radial distribution system is shown in Fig.1.3. The transference of electric power from the transmission system to the distribution system is done by using following equipment[27]-[31]:

a) Substation,
b) Transformers
c) Radial feeders,
d) Bus bar or node and

e) Radial distributor.

f) Service mains

g) Circuit breakers etc.

a) Substation: The system, which transfer's power from the transmission system to the distribution system of a zone or region is called as a substation. The consumer's loads except very large loads can not be connected directly to the main transmission system since it is uneconomical. Hence, the substation is required to be used to step down the voltage to a level, which is appropriate for local service distribution.

b) Transformers: Transformers are located in distribution substation are used to step down the voltages in transmission lines down to primary distribution voltages. Important pieces of equipment that reduce the voltage of electricity from a high level to a level that can be safely distributed to an area, or a residence/business.

c) Radial Feeder: It is a medium voltage line(conductor) used to delivers electric power from a substation to consumer to small substations. The current in the feeders remains constant since there is no tapping of current from the feeder. The current carrying capacity has to be considered to design a feeder.

d) Switch: Control the flow of electricity and steer the current to the correct circuits. It avoids the short circuits between circuits.

e) Busbar: A thick rigid bars of copper strips, which works as a common connection between many circuits and splits the electric power off in multiple directions in distribution lines.

f) Radial distributor: Radial distributor is a line (conductor), which distributes the electric power from bus bar to the consumers along with a single path. The current in the radial distributor is not constant since it taps the current at many locations along its length. The voltage drop along its length is the main consideration while designing a distributor.

g) Service Mains: It is a small line (cable) which carries power from distributor to the terminals of the consumer's load.

h) Circuit Breakers: A circuit breaker is an automatic electric switch which interrupts the flow of current into the distribution substation from the transmission system and distribution lines to protect distribution substation from the damage caused by overload and short circuit currents when a fault occurs.

The electrical distribution system is broadly classified as follows: [32]-[36]

1. According to the nature of current:
   a) A.C. distribution system: these are subclassified into two types
      1). Primary distribution system
      2). Secondary distribution system
   b) D.C. distribution system: these are subclassified into two types
      1). Two-wire DC distribution system
      2). Three-wire DC distribution system

   A.C. distribution system is more economical and simpler than D.C. distribution system. Hence, in recent days, A.C. distribution systems are adopted universally.
2. According to the scheme of connection:
   a) Radial distribution system
   b) Loop distribution system
   c) Network distribution system
3. According to the type of construction:
   a) Overhead distribution system
   b) Underground distribution system

1.1.1. Primary distribution

The primary distribution is one which supplies electric power to various substations per a region or zone. These substations distribute 230 V of power directly to the consumer's load. The primary distribution systems are operated at the voltages higher than the secondary distribution system and handle the energy of the huge block. The voltage levels of the primary distribution system depend on two factors, firstly, the amount of electric power to be carried to the substation and secondly, the distance of the substation. The voltage level of most of the primary distribution systems is ranged between 3.3 kV to

33 kV phase-to-phase and 2.4 kV to 20 kV phase-to-neutral. A single phase and three phase power are drawn by the load from three-phase service. Distribution of Single-phase power happens by primary distribution for light load motors.The primary distribution system usually carried out by three phase three wire system because of the economic considerations. The main advantage of primary distribution is, it distributes power directly to the medium load consumers. Maximum service consumers are connected to the transformers, which step down the distribution voltage to the mains(supply) voltage utilized by interior and lighting wiring systems. The voltage of the primary distribution systems varies according to the need of power supply to the load [37] and [38].

1.1.2. Secondary distribution

It is the part of an A.C. distribution systems which delivers the electrical energy from primary distribution to the ultimate consumer's utilization whose voltage is of 400V and 230V. It is the combination of several distribution substations fed by the primary distribution system. The distribution substations are allocated nearer to the consumer's area or locality and comprise step down transformers. Each substation steps down the voltage to 400V and delivers power to the load by a three phase, four-wire system. The voltage between two phases is 400V and between phase and neutral is 230V. All single-phase residential, commercial and smaller loads are connected between any phase and neutral. However, the large electric motor loads, clothes dryers, and electric stoves are connected between any two phases directly since the three-phase energy is extra capable regarding power delivered per cable. It is necessary to provide a ground connection for the consumer's equipment and the equipment maintained by the utility to shun the consequences abnormal voltages that are occurred due to the occurrence of a fault in distribution transformer and the fall of high voltage lines on the low voltage lines [39-40].

1.1.3. Two-wire D.C. distribution system

It is well known that nowadays, the electric power is virtually generated, transmitted and distributed as A.C. because the magnitude of alternating voltage can be easily and expediently changed using transformers. However, D.C. power is unequivocally required for some applications. For example, for the variable speed D.C. motors, and the industrial storage batteries D.C. power is required. Hence, the motor-generator sets, rotary converters, and rectifiers are used at substations to convert the A.C. power to D.C. power. One of the methods to supply the D.C. power from the substation is “two-wire D.C. distribution system”. The two-wire D.C. distribution system is the system which consists only two wires, one is positive which is called as outgoing wire, and the other is negative which is called as return wire. The Fig.1.4 shows the two-wire D.C. distribution system. In this system, the loads are connected in parallel with the D.C. source across the positive and negative terminal. This system feeds the power to the motor (M), lamp (L) loads and heating circuits. The efficiency of this system is low, so, it is not used to transmit the power but used to distribute the D.C. power [41].

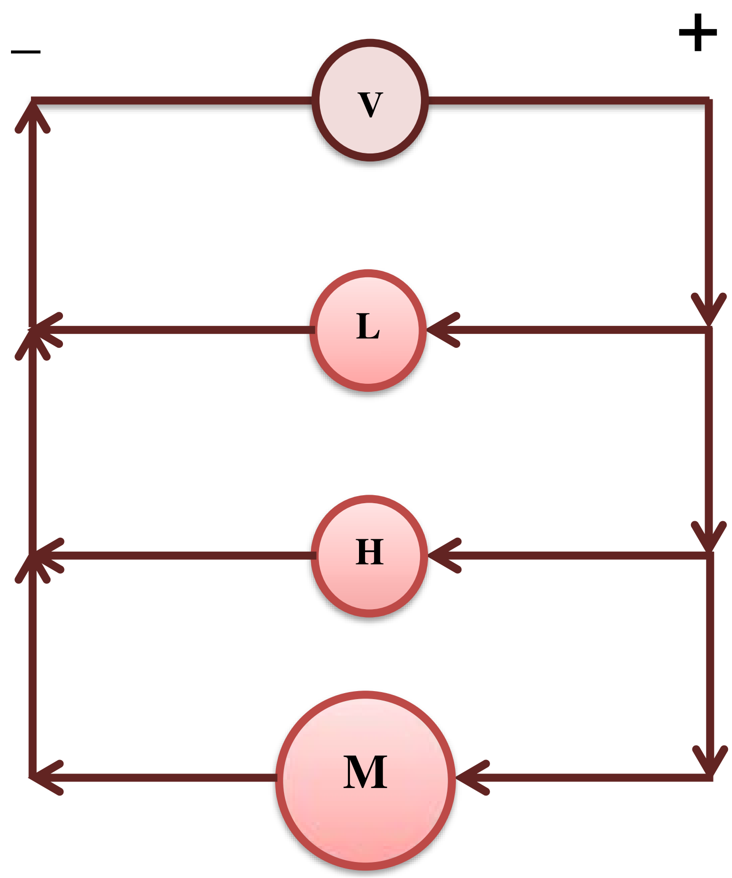

Figure.1.4: Two-wire D.C. distribution system

1.1.4. Three-wire D.C. distribution system

The three-wire D.C. distribution system is a system, which supplies the both high and low D.C. voltages to the consumers. The Fig. 1.5 shows the three-wire D.C. distribution system. This system is designed with two outer wires and one neutral wire. The voltage across to outer wires is 2V, and the voltage across either of one outer wire and the neutral wire is 1V as shown in Fig.1.5.

The motor loads, which requires high voltage, are connected to two outer wires and the lamp loads and heating circuit loads, which requires low voltages, are connected across any outer wire and neutral wire. In this way, the three-wire D.C. distribution system provides two voltage levels to the consumer's load terminals [42].

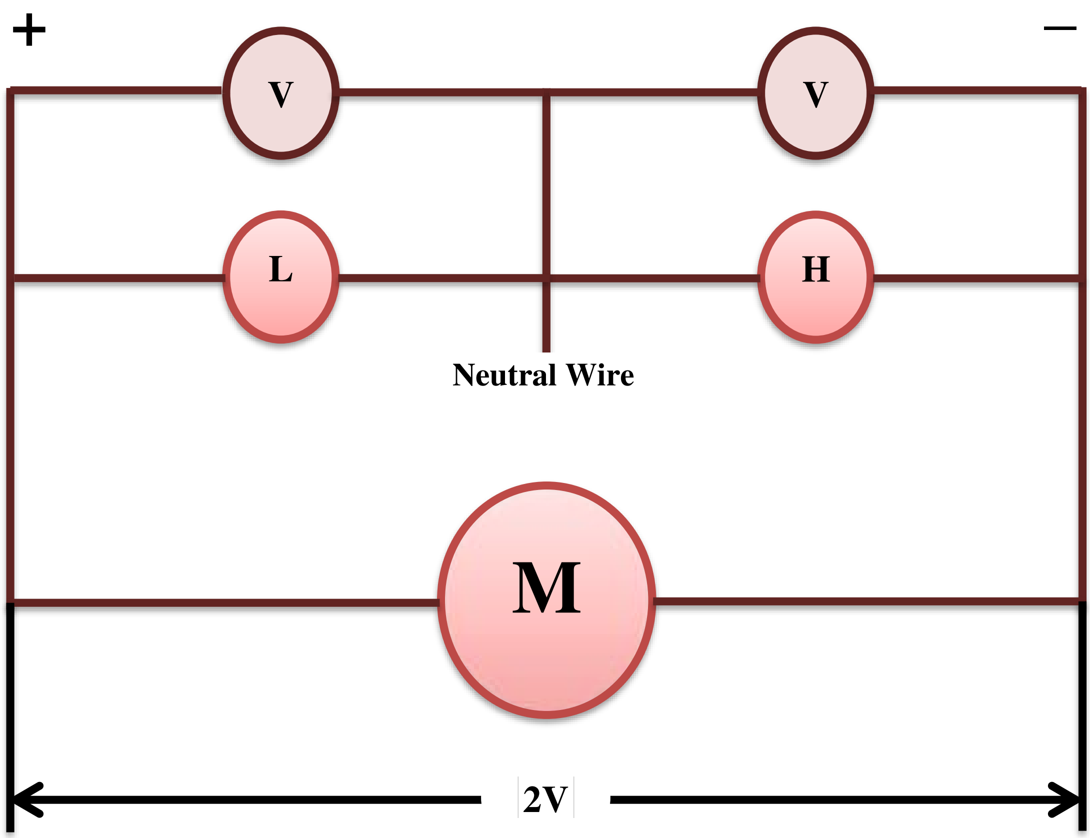

Figure.1.5: Three-wire D.C. distribution system

1.1.5. Radial distribution system

The typical block diagram of the radial distribution system is shown Fig. 1.6. This system is the most economical to establish and is extensively used in lightly populated regions. The radial distribution system has a single electric power source for several consumer's loads as shown in Fig. 1.6. The power flows from the substation to the load along a single path. In this system, the distributors are fed at only one end by a feeder that is radiated from the only one substation. This system is useful only when the substation is located at the midpoint of the loads and generating the low voltage power [43].

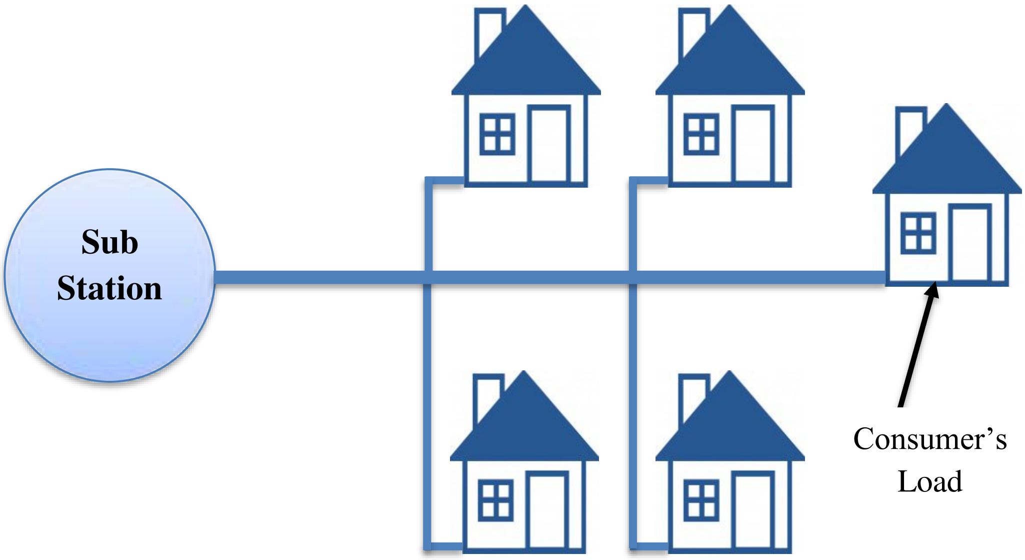

Figure.1.6: The typical diagram of radial distribution system

Advantages of radial distribution system:

1) Simple in designing, planning, and operation
2) Low initial investment cost and economic system

Disadvantages of radial distribution system:

1) A short-circuit, power failure and downed power line will cause power interruption to all consumers who are on the fault side from afar the substation since they are dependent on single distributor and feeder.

2) The end of a distributor gets heavily loaded since it very near to the distribution substation.
3) The consumers connected to the distributors' would face severe voltage variations when the load on the distributor changes.

1.1.6. Loop distribution system

The loop distribution system, as the name designates, makes a loop circuit from the substation, bus bars, primary windings of distribution transformers and through the whole load area to be supplied and returns to the original point(substation). In this system, two substations or power sources are tied in the loop to supply the power to the consumers from both(either) directions by the placement of switches in planned locations. The loop distribution system can also be called as ring distribution systems. The Fig.1.7 shows the loop distribution system [44].

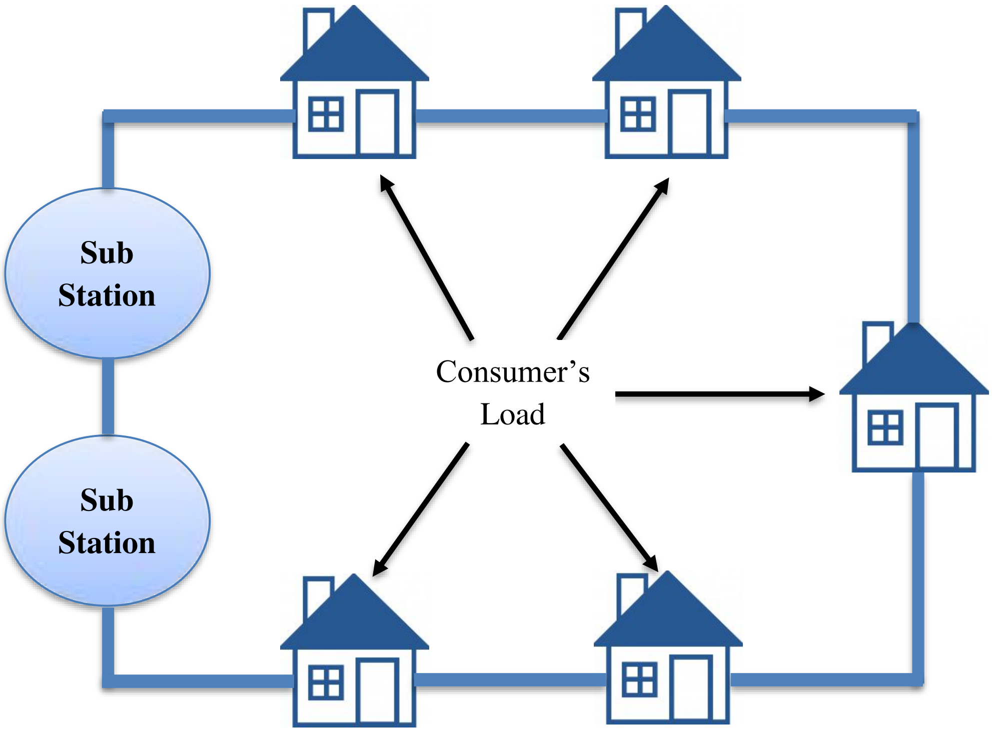

Figure.1.7: The typical diagram of loop distribution system

Advantages of loop distribution system:

1) This system is more reliable than radial distribution system as the consumers are fed by from another source in the loop by automatic or manual operation of switches when one source in the loop gets failed to supply power.
2) This system offers better continuity of service than the radial distribution system, except the presence of short power interruptions while switches are being operated during the power failures due to faults occurred on the line.
3) As it happened that power fails because of faults, the utility can restore the power supply as soon as it finds the fault because the fault can be revamped immediately with short power interruption to the consumers.

Disadvantages of loop distribution system:

1) The initial investment cost of the system is high compared to radial distribution systems since this system requires many conductors and switches.

1.1.7. Network distribution system

Network distribution system is the system in which the feeder loop is powered(energized) by two or more substations or generating stations. Network distribution system is an interlocking loop system and is more complicated compared to remaining systems. These systems used only in downtown regions, congested, and high load municipal areas. The typical diagram of network distribution system is shown Fig. 1.8. Any area can be fed from two generating stations simultaneously during peak load hours which causes the efficiency of the system to be increased and the reserve power capacity of the network distribution system to be reduced.

Advantages of network distribution system:

1) This system is more reliable than radial and loop distribution systems since this system comprised with two or more substations.
2) The efficiency of this system is high compared to radial and loop distribution systems.

Disadvantages of network distribution system:

1) This system is more expensive than radial and loop distribution systems.
2) This system is not simple in designing, planning, and operation.

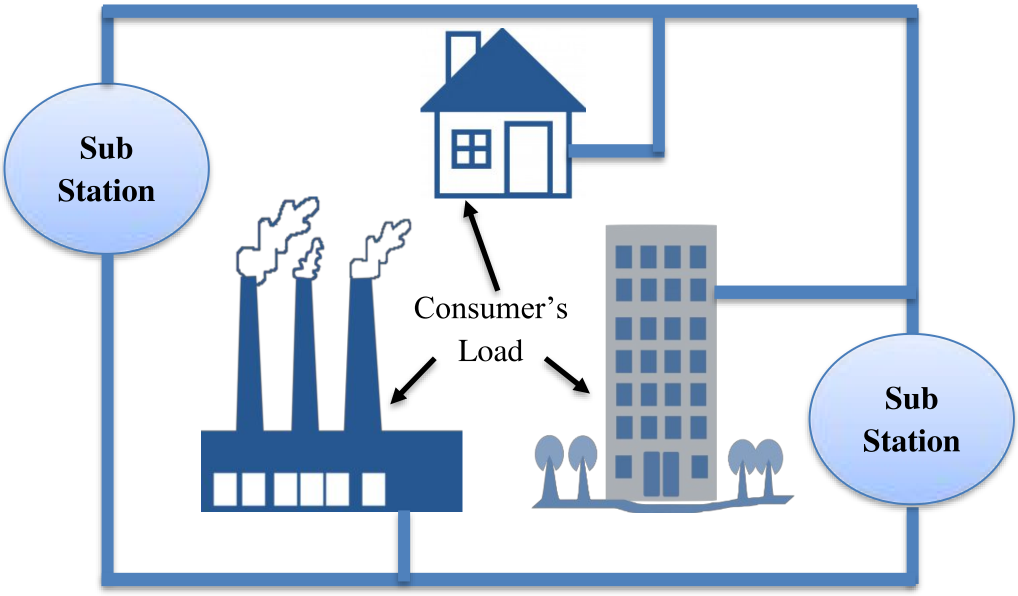

Figure.1.8: The typical diagram of Network distribution system

1.1.8. Classification of buses in distribution systems

The concept of buses in electric distribution systems is very much essential for the load flow studies. The principal aim of the load flow studies is to evaluate the magnitude of the voltage at each bus, and it's phase angle when the generated power and loads are already specified. During the evaluation of load flow studies some assumptions are essential to consider such as the loads are defined by their active and reactive power consumption, the loads are treated as constant, and the terminal voltage of the generator is constant since the voltage is strongly regulated. To enable the load flow studies in various applications the buses of the power system have been classified as follows [45]-[47]:

a) P-Q bus or Load bus

b) P-V bus or voltage controlled bus or Generator bus

c) V-|δ| bus or reference bus or swing bus or Slack bus

a) **P-Q bus or Load bus:** The bus in which no generators are connected is called as P-Q bus. The active power (P_{Gi}) and reactive power (Q_{Gi}) are considered as zero since there is no any generator connected. The active and reactive loads connected to this bus is denoted by $-P_{Li}$ and $-Q_{Li}$ respectively. The negative sign signifies that the direction of power flow happens from the bus to the load. The load bus can also be called as load bus. The principal aim of the load flow in this bus system is to evaluate the magnitude of bus voltage $|V_i|$ and its phase angle δ_i.

b) **P-V bus or voltage controlled bus or Generator bus:** The bus in which the generators are connected is called as P-V bus. The power generation and terminal voltage in P-V bus system are controlled by using prime mover and the generator field excitation respectively. In these bus system the value of P_{Gi} and $| V_i |$ can be specified constant by keeping the bus voltage and input power constant using an automatic voltage regulator and turbine governor control respectively. Hence, these bus system is called as P-V bus. The p-v bus is also be called as voltage controlled bus or generator bus. The reactive power(Q_{Gi}) supplied by the generator can not be specified in advance since it depends on the configuration of the system. The principal aim of the load flow in this bus system is to find the unknown bus voltage phase angle (δ_i).

c) **V-|δ| bus or reference bus or swing bus or Slack bus:** The bus, which sets the reference angle for all remaining buses in the system, is known as V, |δ| bus. This bus is also called as a slack bus or reference bus. This bus is the very essential for the load flow studies without which load flow studies are meaningless. However, the angle of the slack bus is not important for load flow studies since the active and reactive power between two voltage sources can be dictated by the difference between the phase angle of the two voltage sources. Hence, the angle of the slack bus is preferred as 0°. Also, the voltage magnitude of the slack bus is assumed as prespecified value.

1.3. Research background on electrical distribution systems

Recent years the planning of distribution systems are prominently essential in power system because of the wide variations in the strategies of the power supply [48], [49]. The operation of electrical power distribution system is subjected to high power losses due to high resistance to reactance ratio [50] as compared to high voltage transmission systems, i.e. due to lower operating voltage and hence high current [51]. Also, suffers from line loadability, poor voltage profile at the end nodes and poor voltage stability, etc. [52]-[56]. Since distribution systems are suffering from high power losses, it is a challenge to the utilities to plan distribution systems to provide power for the cheapest possible rate and to serve reliable and good quality of electrical power to the distributed consumers in the present competitive environment [57]. Hence, it is important that the distribution companies (DISCOs) should design RDNs properly to optimize their operation and the energy loss, voltage profile, and voltage stability, etc. [58], [59]. Thus, the utilities are adopting various advanced strategies to mitigate these problems by compensating the reactive power in the distribution system.

The reactive power compensation schemes, such as capacitor bank placement [60], on load tap changers [61], combinatorial operation of capacitor banks and on load tap changer [62] and [63], incorporation of DG (distributed generation) [64] and [65], etc. can reduce the power loss and improve the voltage profile and stability etc. Switched shunt capacitors are optimally placed in a radial distribution system in a fuzzy multi-objective approach by using a genetic algorithm (GA) to maximize the net savings and to minimize energy loss and voltage drop [66]. Capacitor banks are optimally placed in the distribution systems to reduce power loss in [67]. The optimal capacitor placement using particle swarm optimization is reported in [68]. Cuckoo search optimization technique applied to capacitor placement on distribution system problem [69]. However, capacitors are not capable of providing smooth reactive power compensation and suffering from inevitable oscillations along with the inductive elements in a system [70]. The optimally distributed generation allocation and sizing in distribution systems via artificial bee colony algorithm has been investigated in [71]. DGs are used for the DN to optimize the energy loss and benefit–cost analysis of DG installation by optimally sizing and allocating it on DN [72] - [75]. However, DG sources are relatively high costs, and intermittency [76] - [79].

Nowadays, DFACTS (distribution FACTS) devices such as Unified Power Quality Conditioner (UPQU), static VAR compensators (SVC), Distribution static synchronous series compensator (DSSSC) and distribution static synchronous compensator (DSTATCOM) etc. [56] and [122] are used for the reactive power compensation, because of the rapid advancement of power electronic devices. A comprehensive review has been done on optimization techniques for the placement and sizing of custom power devices in RDNs [80]. UPQC is used to compensate the reactive power in radial distribution systems

[81], and the impact of its online allocation loading, losses, and voltage stability is investigated in [82]. A multi-objective planning strategy for UPQC allocation by minimizing three objective functions, such as the rating of UPQC, system power loss, and percentage of nodes with under voltage problem is provided in [83] to determine its optimal location(s) and size(s). A state-of-art review on the different reactive power compensation techniques including the allocation strategies of custom power devices, such as SVC is reported in [84]. DSSSC (distribution static synchronous series compensator) is used to reduce the power loss and to enhance the voltage profile in RDNs [85]. Some of the power quality issues of electrical distribution systems influenced by the allocation of DSTATCOM with distribution generator are given in [86]. These devices are optimally sized and allocated in the radial distribution system by using a particle swarm optimization algorithm to compensate the reactive power for the reduction of power loss [87]. The optimal allocation of DSTATCOM along with network reconfiguration by using differential evolution algorithm is carried to minimize the power loss of radial distribution systems in [57]. Modeling and optimal allocation for DSTATCOM for the compensation of reactive power in radial distribution systems are presented in [88]. The reactive power is compensated by using DSTATCOM for distribution systems with wind energy in [89]. By using the combination of both DVR & DSTATCOM, the voltage sag is mitigated with and without injection of real and apparent power in RDN when faults are occurred [90]. The combination of optimal operation and network reconfiguration of the distribution system is a complicated problem [92] since the network reconfiguration results in a change in topology of feeder structure by opening or closing of sectionalizers. Moreover, the control of DSTATCOM with DG in the distribution systems is complex, and a DVR is costlier as compared to a DSTATCOM [57]. However, the installation and maintenance costs of combinatorial schemes are high and complexity in operation [91].

Among all these devices discussed above DSTATCOM has several advantages such as reduces the system power loss with reactive power exchange, high regulatory capability, low compact size and low cost and less harmonic production and does not have any transient harmonic operational problems. Also, DSTATCOM mitigates the power quality problems such as voltage fluctuations, voltage sag, unbalanced load, and voltage unbalance and. [123] and [124]. A distribution static compensator (DSTATCOM) is a power electronic based synchronous VSC (voltage source converter) that generates an AC voltage by a short-term energy stored in a DC capacitor. The reactive power exchange between the device and the distribution system can be controlled by controlling the magnitude of the voltage at D-STATCOM [125] and [126].

Hence, In view of all these problems, it is interesting to investigate the impact of optimal allocation of single and multiple DSTATCOM in RDS to optimize voltage profile, power loss, total planning cost of energy loss per annum or energy loss cost (ELC). Modeling, sizing, and allocation of single DSTATCOM on radial distribution systems to optimize the power loss and improve the voltage profile by compensating the reactive power are investigated in [56], [68], [70], [73], and [93]-[96].

1.4. Motivation

There are several factors that encouraged deciding this topic for the thesis. Still, the primary sources of motivation for this work are:

1. Distribution systems are traditionally suffering from high power loss compared to transmission systems, poor voltage profile. These problems are causing the poor power quality in the supply of power to the consumers.
2. Most of the previous investigations introduced the allocation of capacitors and combinatorial devices to compensate the reactive power in RDS to reduce power loss and improve voltage profile. But, capacitors are incapable of providing smooth reactive power compensation and suffering from inevitable oscillations along with the inductive elements in a system.
3. Combinatorial devices as mentioned in section 1.2 used for the reactive power compensation in radial distribution systems to minimize power loss are not economical and increases the complexity of control and operation of the device and system.
4. Very few investigations have been contributed in recent days to optimize the energy loss cost of RDS per annum and PH with the optimal allocation of appropriate DSTATCOM model.

5. New work on Multiple DSTATCOM required to be investigated since the distinct combinatorial devices are not economical and increase the complexity of control and operation.

In view of all these problems, it is interesting to investigate the impact of optimal allocation of single and multiple DSTATCOM on RDS to optimize the voltage profile, power loss, the energy loss cost, total net profit or economic benefit per annum and PH.

1.5. Objectives of thesis

1. Devising a new modeling of DSTATCOM to incorporate it in RDS.
2. Developing FBS load flow algorithm and incorporation of DSTATOM in FBS algorithm.
3. Formulation of the objective function to evaluate the objectives of proposed approach such as the power loss, voltage profile, energy loss cost, total net profit per annum and PH.
4. Development of ESM algorithm to find the optimal allocation and rating of DSTATCOM in radial distribution systems to optimize the power loss, voltage profile, energy loss cost, total net profit per annum and PH.
5. Development of DEA algorithm to find the optimal allocation and rating of DSTATCOM in radial distribution systems to optimize the power loss, voltage profile, energy loss cost, total net profit per annum and PH.

1.6. Work done

In this Thesis, a new phase angle model for DSTATCOM based on optimal angle injection (DSTATCOM-OAI) is developed. In the proposed model, the rating of the DSTATCOM is determined with the injection of the optimal phase angle of the voltage phasor at the location, in which a DSTATCOM is placed. The DSTATCOM model is suitably incorporated into the FBS load flow algorithm [97] to minimize total active power loss. Exhaustive search and Differential Evolution (DE) algorithm [98] - [101] is used to determine the optimal locations and sizes for DSTATCOM, ELC, and total net profit (TNP) in RDS. The IEEE-30, 33 and 69 node radial distribution system are used as test systems o demonstrate the proposed approach, and it is noteworthy that there is a significant reduction in power loss and ELC and improvement of voltage profile and TNP after the placement of DSTATCOM on the radial distribution system. The results of the proposed approach are found to be better as compared to approaches reported in [51], [31], [87], [88], [102], and [103].

1.7. Thesis organization

The entire thesis is divided into seven chapters. The organization of the thesis and a brief chapter wise description of the work presented are as follows:

Chapter 1 provides the overview of electrical distribution systems and their classifications with merits and demerits. The different power quality issues occurring in electrical distributions systems are discussed. The previous investigations upon solving some of the power quality issues are discussed. Why the need for research in electrical distribution systems has been studied based on previous research background. This chapter provides the strong reasons that what motivates the author to opt the proposed approach. The objectives and contributions of the proposed approach are mentioned in this chapter.

Chapter 2 discussed the development of new phase angle model of DSTATCOM and its incorporation in FBS algorithm. The FBS algorithm and flow chart developed are provided in this chapter. Also, the principle of operation of DSTATCOM is described.

Chapter 3 proposes the distribution STATCOM with optimal phase angle injection model for reactive power compensation of radial distribution systems using DEA and ESm techiniques. Firstly, the brief disruption on ESM and is algorithm in proposed approach are described. Secondly, Overview and flow chart of DEA and the optimal allocation of DSTATCOM using DEA are provided in this chapter. The solution strategy of DEA and the comparative simulation results and exhaustive search results are discussed in this chapter.

Chapter 4 deals with the optimization of energy loss cost of distribution systems with the optimal placement and sizing of DSTATCOM using differential evolution algorithm. mathematical problem formulation i.e. objective function (F), real power loss, present worth factor (PWF) analysis, TNP/Savings, constraints, solution strategy using DEA, simulation results, impact of DSTATCOM allocation, analysis of power loss reduction, analysis of ELC are discussed.

Chapter 5 investigates optimal phase angle injection for reactive power compensation of distribution systems with the allocation of multiple distribution STATCOM and the combination of DSTATCOM and DG. Why for multiple DSTATCOM allocations, results of multiple-DSTATCOM allocation using DE, Comparative results with some of the previous works, and the solution obtained with proposed de algorithm, in 50 runs for the 69-node system are discussed.

Chapter 6 concludes the thesis by summarizing the contributions and conclusions of all the chapters. Ultimately, the final section explores future directions of research that emerged as an outcome of the work presented in this thesis.

Chapter 2

Phase angle model of DSTATCOM and its Incorporation in FBS algorithm

2.1. Introduction

This chapter presents the principle of operation of DSTATCOM and the new phase angle model of DSTATCOM devised and its incorporation in FBS algorithm to investigate the impact of its placement on power loss reduction, cost of energy loss and voltage profile.

In a distribution system, there may be several different compensating devices. However, in a radial distribution system, the voltage profile of a particular bus can be poor or distorted or unbalanced if the demand is increased suddenly or loads in any part of the system are nonlinear or unbalanced. The power quality problems in the DS usually originate from voltage disturbances and power loss. In DS the maximum amount of power gets consumed by the reactive loads, as a result there is increase in lagging power factor current drawn by these loads. Hence, the demand of excessive reactive power increases, which causes the reduction in the capability of active power flow, increase in power loss and poor voltage profile. Therefore, in recent days the voltage profile and power loss predominantly play vital role in the planning and operation of DS. Thus, the main reason of poor voltage profile and power loss in DS is the excessive demand of reactive power and increase in load. The DSTATCOM, which belongs to the family of DFACTS devices can compensates the reactive power statically in the DS to minimize the power loss and improve the voltage profile.

Before entering into the discussion of the new phase angle model of DSTATCOM and its incorporation in load flow algorithm for achieving the objectives of the proposed approach, it is very much essential to know what is the operation of FBS load flow algorithm, and why and how it’s used in the proposed approach and what is DSTATCOM, what are the components used in the design of DSTATCOM, how the working principle of DSTACOM involved in proposed approach.

2.2. DSTATCOM in the proposed approach

2.2.1. What is DSTATCOM?

DSTATCOM is a fast response solid-state power electronic based shunt controlled voltage source converter (VSC) which injects the current to the utility feeder or nodes in distribution systems for the smooth reactive power compensation to improve the power quality in DS such as enhancement of the voltage profile and minimization of the power loss of the DS [104]-[106]. Mainly it consists of an inverter, which works on the principle of self-commutation control. The output voltage of the DSTATCOM can be controlled according to the requirement of the reactive power since it is a voltage-sourced converter. The DSTATCOM can be called in other words that it is a distribution static synchronous condenser (DSTATCON). Usually, this device is sustained by a DC energy storage capacitor. It generates the inductive and capacitive reactive power according to the load demand to meet the specifications of utility[104].

2.2.2. Components involved in DSTATCOM design

The DSTATCOM consists of an IGBT based VSC (voltage source converter), DC storage capacitor and a coupling transformer as shown in Fig. 2.2

1) **Voltage Source Converter(VSC):**

   VSC is used to convert the DC input voltage to an AC output voltage at fundamental frequency and generates or absorbs the reactive power.

2) **DC storage capacitor or energy storage device:**

   DC storage is used to supply constant DC voltage to the voltage source converter (VSC) via a DC link capacitor for the generation of injected voltages.

3) **Coupling transformer:**

   A coupling transformer is one, which couples two different voltage signals. It couples the output voltage of VSC and bus voltage of DS voltage through the reactance. In addition, the inductive reactance of transformer minimizes ripples contained in the compensating currents produced by VSC. The inductive reactance of transformer can also be called as interfacing reactance. Coupling transformer used at AC side of VSC as shown in Fig. 2.2. The coupling transformer can also provide isolation between the inverters of multilevel inverter structure, which avoids the DC storage capacitor from being short-circuited with the inverters through switches.

2.2.3. Working principle of DSTATCOM

In this section, the working principle of DSTATCOM according to its application in the approach proposed in thesis is elaborately discussed. In the proposed approach, DSTATCOM is used for reactive power compensation in DS to reduce power loss and improve voltage profile.

The Basic Arrangement of DSTATCOM is as shown in Fig.2.2. The reactive power exchange between the DSTATCOM and DS can be regulated by varying the output voltage of DSTATCOM (VSC), so that the DS voltage profile be improved. DSTATCOM in general is an IGBT based VSC. The principle of operation of DSTATCOM is same as to the operation of a rotating synchronous electrical machine without the mechanical inertia, which either absorbs or generates the reactive power in synchronization according to the demand. Hence, DSTATCOM is called as a distribution static synchronous compensator.

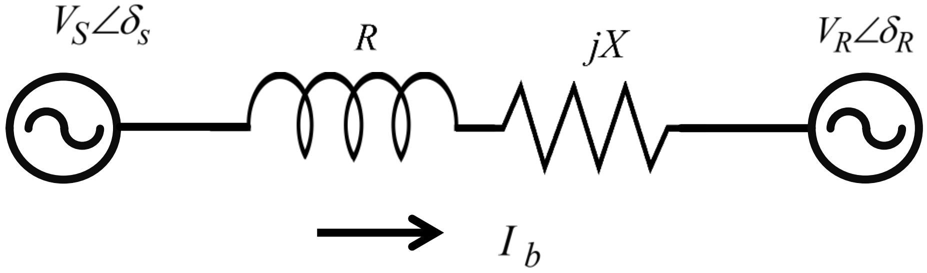

Figure.2.1: A simple line diagram of an electric line connected between two consecutive voltage sources

First of all the phenomenon of the reactive power transfer equation is described before the principle of operation of DSTATCOM is discussed so that it would be understood very easily. As shown in Fig. 2.1 two voltage sources V_S and V_R that are connected each other through an impedance $Z = R + jX$, and the current flowing through the impedance branch is I_b are considered. The resistance R is assumed to be as zero and the difference of angle between V_S and V_R is 'δ' expressed by Eq. (2.1).

$$\delta = \delta_S - \delta_R \tag{2.1}$$

The active power flow exists between the two voltage as shown in Fig.2.1 is expressed by Eq. (2.2)

$$P = \frac{V_S V_R}{X}\left(Sin\left(\delta\right)\right) \tag{2.2}$$

Similarly, the reactive power flow exists between the two voltage is given in Eq. (2.3)

$$Q = \frac{V_R}{X}\left(V_S Cos\left(\delta\right) - V_R\right) \tag{2.3}$$

If the 'δ' is 'zero' then the active and reactive, power becomes as given Eqs. (2.4) and (2.5) respectively:

$$P = 0 \tag{2.4}$$

$$Q = \frac{V_R}{X}\left(V_S - V_R\right) \tag{2.5}$$

From Eqs (2.4) and (2.5) it is very clear that if the difference of angle between V_S and V_R is zero, the active power (*P*) flow becomes zero and the reactive power (*Q*) flow depends on 'V_S -V_R'. Hence, the reactive power flow in the system happens in two ways. Firstly, if the voltage V_S is greater than V_R, then the reactive power flow happens from the source V_S to V_R. Secondly, if V_R is greater than V_S, then reactive power flow happens from the source V_R to V_S. This same principle is applied in the working principle of DSTATCOM.

Now it is very easy to understand how the working principle of DSTATCOM. A typical RDS, as shown in Fig. 2.2. is considered for the implementation of DSTATCOM operation. It consists of '*n*' number of buses connected to a stiff voltage source at bus 'V_1'. There is a load connected at each bus and are supplied by respective buses. Based on the reactive power need of utility or particular customer the DSTATCOM is subjected to be connected in any bus. E.g. if the voltage '$V_{3\ (BUS)}$' is disturbed, all buses except slack bus will be affected, and then the utility installs a DSTATCOM at 'bus 3' to mitigate the voltage problem. If the same happens with consumers load then the consumer installs the DSTATCOM in the premises of the problem occurred.

Let '$V_{3\ (BUS)}$' be the bus voltage of DS and '$V_{DSTATCOM}$' be the output voltage of the DSTATCOM as shown in Fig. 2.2. The reactive power flows only when the angle between two voltages is zero i.e. '$V_{DSTATCOM}$' is in phase with '$V_{3\ (BUS)}$' during steady state condition.

The reactive power exchange is zero if the magnitude of '$V_{3\ (BUS)}$' is equal to '$V_{DSTATCOM}$', as a result the DSTATCOM neither generate nor absorb the reactive power. The flow of reactive power is discussed in two modes of operations, which is also called as voltage regulation mode such as:

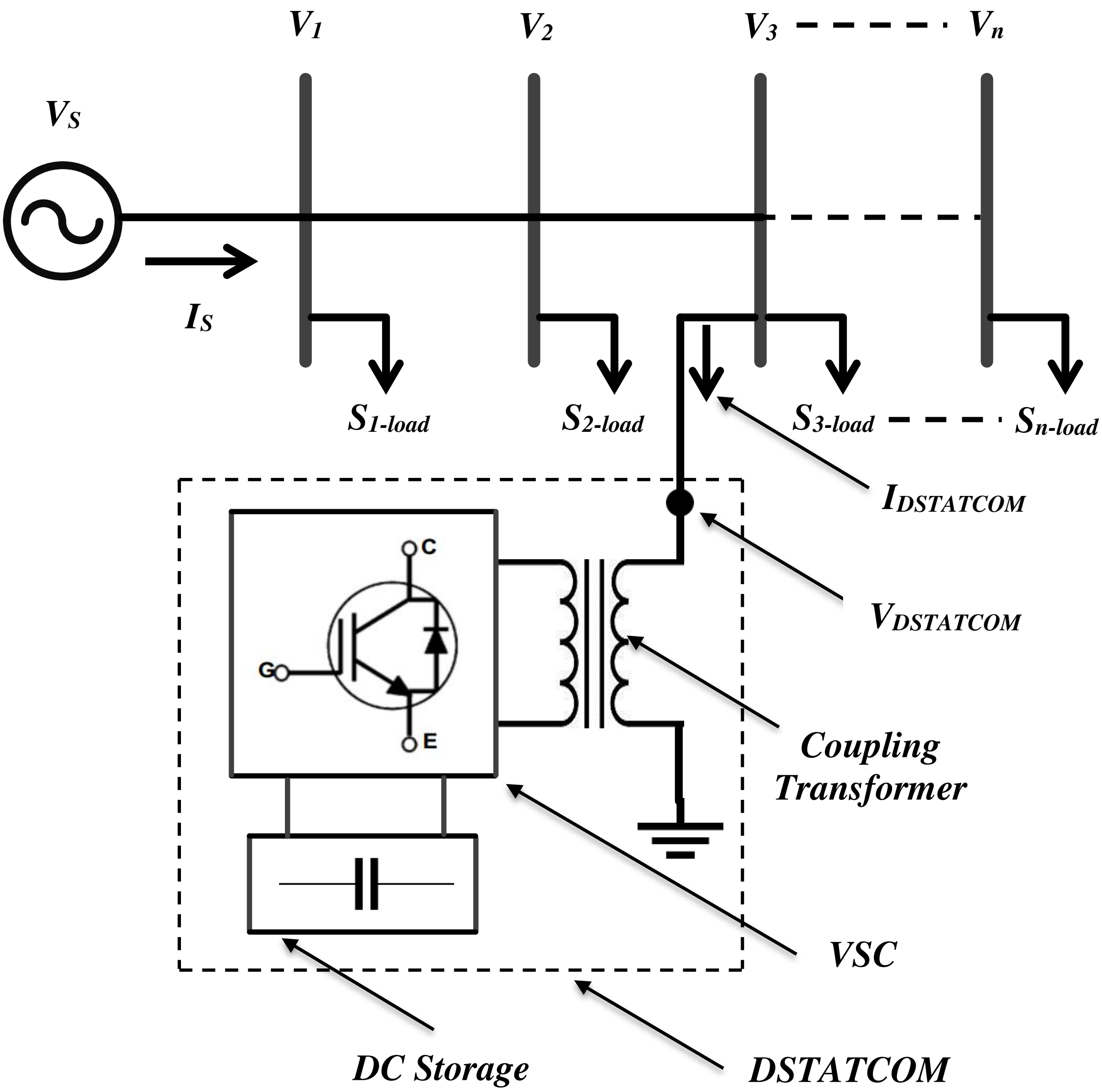

Figure.2.2: A simple Radial distribution line with the allocation of DSTATCOM

1) Inductive mode or Q-generation
2) Capacitive mode or Q-absorption.

1) Inductive mode or Q-absorption

If the magnitude '$V_{DSTATCOM}$' is less than '$V_{3\ (BUS)}$', the DSTATCOM, feels the capacitive reactance connected at its output terminals, simultaneously the DS feels the inductive reactance at the *PCC* where the DSTATCOM is connected. Hence, the

DSTATCOM current '$I_{DSTATCOM}$' lags behind the voltage of DS exactly by an angle of 90º as shown in Fig.2.3 and allows the DS currents to flow into it, which causes the DSTATCOM to absorb reactive power. That is how, the reactive power flows from DS to DSTATCOM through the coupling transformer. Thus, the DSTATCOM absorbs the reactive power. Generally, this mode occurs when the bus voltage of DS increased due to load throw off or some other abnormal situations. At this situation, DSTATCOM reduces '$V_{DSTATCOM}$' and therefore absorbs the reactive power so that the voltage reaches to its normal value. The time diagram of the DSTATCOM voltage and current during this mode of operation is shown in Fig.2.3

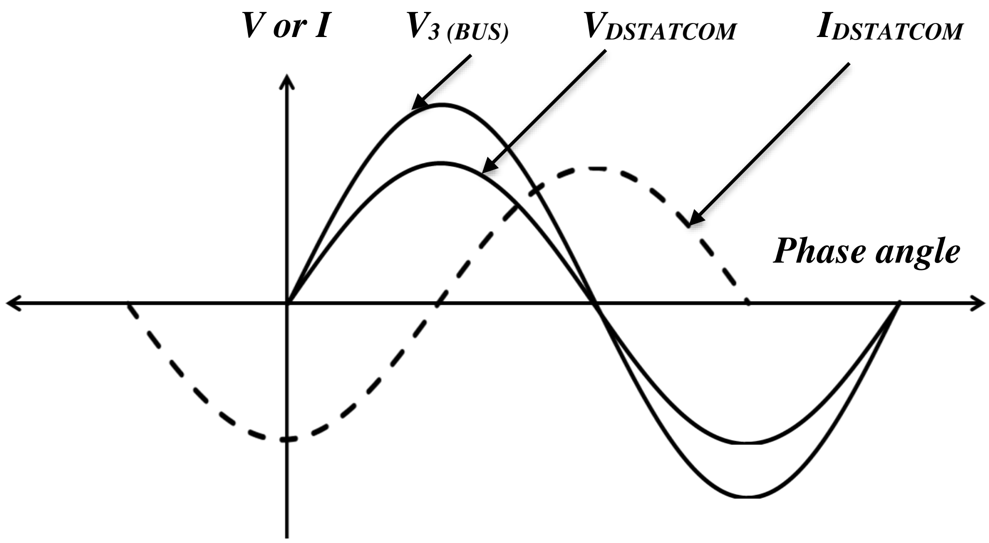

Figure.2.3: The time diagram of DSTATCOM voltage and current in inductive mode of operation (absorption of Q)

2) Capacitive mode or Q-generation

If '$V_{DSTATCOM}$' is greater than '$V_{3\,(BUS)}$' the DSTATCOM, feels the inductive reactance connected at its output terminals, simultaneously the DS feels the capacitive reactance at the *PCC* where the DSTATCOM is connected. Hence, the DSTATCOM current '$I_{DSTATCOM}$' leads the voltage of DS exactly by an angle of 90º as shown in Fig.2.4 and gets injected into the DS which causes the DSTATCOM to generate reactive power. That is how, the reactive power flows from DSTATCOM to DS through the coupling transformer. Thus, the DSTATCOM behaves like as reactive power (*Q*) generator. Usually, this mode occurs when the reactive power demand increased in the DS. At this situation, DSTATCOM increases its output voltage '$V_{DSTATCOM}$'. The time diagram of the DSTATCOM voltage and current during this mode of operation is shown in Fig.2.4.

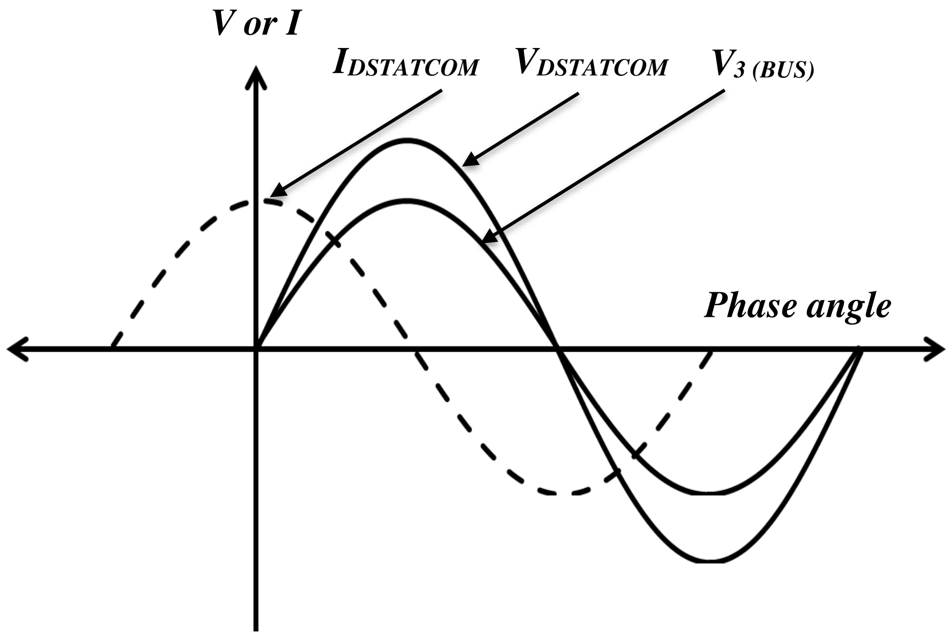

Figure.2.4: The time diagram of DSTATCOM voltage and current in capacitive mode of operation (generation of Q)

In both the modes of operation, it is essential to keep up the difference of phase angle between '$V_{3\,(BUS)}$' and '$V_{DSTATCOM}$' to be zero. However, there exist always the small value of phase difference '$V_{3\,(BUS)}$' and '$V_{DSTATCOM}$' to supply the drop of leakage impedance in the coupling transformer). Thus, the reactive current injection by DSTATCOM depends on the difference between the voltages of DS and the DSTATCOM. Hence, the injection of reactive current by DSTATCOM can only be controlled by the capability of VSC and is independent of system voltage variation.

DSTATCOM can also generate real power to the DS with the help of DC storage device. The DC storage device in the DSTATCOM assembly is located at its input side and the coupling transformer is located on its output side. The exchange of active power can be done by regulating the phase angle of the '$V_{3\,(BUS)}$' and '$V_{DSTATCOM}$'. The DSTATCOM absorbs the real power from the DS if the phase angle of '$V_{3\,(BUS)}$' leads the voltage phase angle of the '$V_{DSTATCOM}$'. The DSTATCOM generates the real power to the DS, if the phase angle of '$V_{DSTATCOM}$' leads the voltage phase angle of the '$V_{3\,(BUS)}$'. However, this phenomenon is very trivial to use practically.

2.2.4. Limitations in the operation of DSTATCOM

Every system or device in the universe has its own limitations. DSTATCOM also has the limitations in absorbing or generating reactive power (Q). The limitation is caused due to the current carrying capacity of IGBT based force-commutated VSC. DSTATCOM neither increase nor decrease '$V_{DSTATCOM}$' or the generation of reactive power as soon as it reaches its limitations. At this situation, either it absorb or generate fixed reactive power at a fixed current or voltage corresponding to its limiting value and behaves like a constant CSI (current source inverter). At this stage, DSTATCOM enters into VAR Control Mode of operation. However, the DSTATCOM has a very low capability to generate active power since it depends on its input DC storage device.

2.2.5. Advantages of DSTATCOM

The DSTATCOM protects the DS from voltage problems such as flickers, sags and swells when the system undergoes the quickly fluctuating reactive current demand due to the unbalanced and sudden variations load. It helps the system to maintain the rich voltage profile to keep the system stable [109].

1) The DSTATCOM exchanges the reactive power required in the distribution system as per the level of system voltages, so that the voltage sensitive loads can be protected.
2) The DSTATCOM provides leading or lagging reactive power factor to correct the power factor of the system.
3) The DSTATCOM requires a very small size of reactive energy storage device to generate reactive power since it has flexibility to employ the modern power electronics based converters within itself less
4) The DSTATCOM is fast response VSC offers improved quality power to the utility or consumers loads.
5) The DSTATCOM capable to compensate not only the reactive power but also, it can control the active power when a suitable DC energy source is available.
6) The DSTATCOM is an encapsulated VSC that reduces environmental influence on the device.

2.3. The new phase angle Model of DSTATOCM

As discussed above the DSTATCOM is a shunt connected VSC device that absorbs or injects both active and reactive current respectively through PCC [70]. In the proposed approach, DSTATCOM is used only for reactive power compensation in DN to improve the voltage profile and minimize the power loss and coast of energy loss cost.

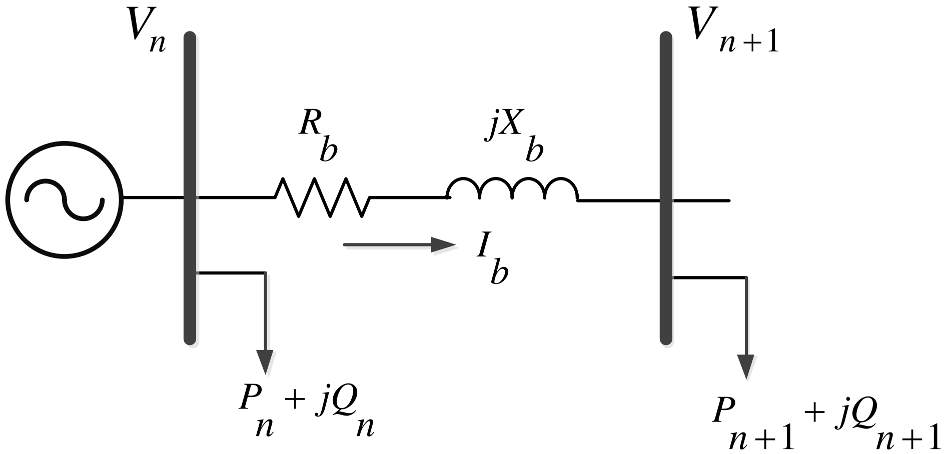

Figure.2.5: Two successive buses of DN drawn as a single line diagram

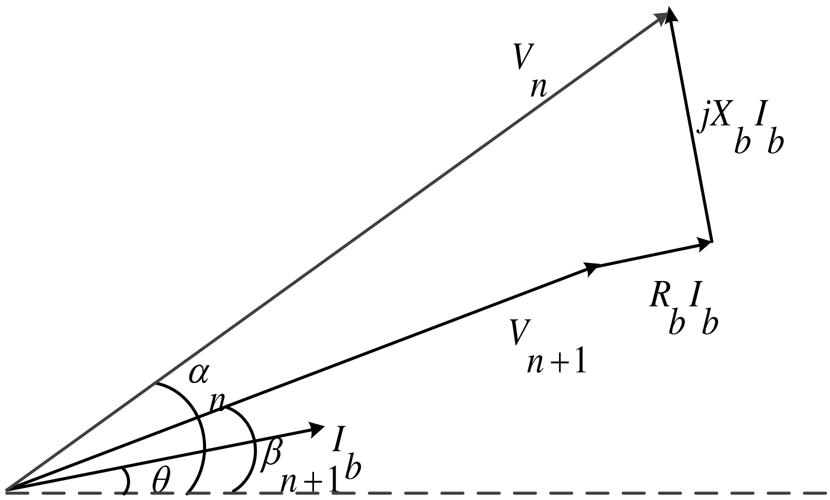

Figure.2.6: Phasor diagram for the network shown in Fig.2.5

Fig. 2.5. is the single line diagram of two successive buses *n* and *n*+1 of DN and there are real and reactive power demands connected to these buses, and it is used to place the DSTATCOM in DN. The Kirchhoff's voltage law equation of the Fig.2.5. is given by Eq.(2.6).

$$\overline{V}_{n+1}\angle\beta_{n+1}=\overline{V}_n\angle\alpha_n-\left(R_b+jX_b\right)\overline{I}_b\angle\theta \qquad (2.6)$$

In above Eq. (2.6), R_b+jX_b is the line impedance between two nodes, V_n is the voltage at the n^{th} node, α_n is the phase angle of V_n, I_b is the line current between the two nodes n and n+1, and θ is the phase angle of I_b. P_n and Q_n are the active and reactive power loads at node n. Fig. 2 is the phasor representation of the Eq. (2.6).

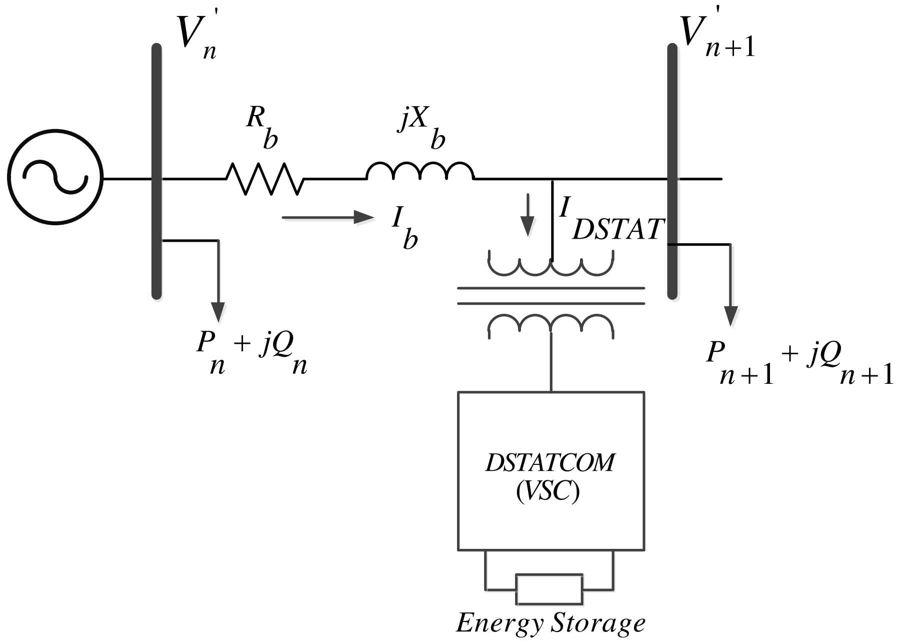

Figure.2.7: Single line diagram with a DSTATCOM placed at bus n+1

To develop the phase angle model of DSTATCOM, it is allocated at node n+1 as shown in Fig. 2.7. The KVL of single line diagram after the placement of DSTATCOM is expressed in Eq. (2.7).

$$\overline{V}_{n+1}^{'}\angle\beta_{n+1}^{'}=\overline{V}_n^{'}\angle\alpha_n^{'}-\left(R_b+jX_b\right)\left(\overline{I}_b\angle\theta+\overline{I}_{DSTAT}\angle\left(\frac{\pi}{2}+\beta_{n+1}^{'}\right)\right) \qquad (2.7)$$

The phasor diagram corresponding to the Eq. (2.7) is shown in Fig. 2.8. With the allocation of DSTATCOM at node n+1 through *PCC*, the voltage at node n+1 is reformed as $V^{'}_{n+1}$ due to the injection of phase angle. The Eq. (2.7) is the main essence for developing the phase angle model of DSTATCOM. The angle of the I_{DSTAT} is expressed as follows

$$\overline{I}_{DSTAT}=\frac{\pi}{2}+\beta_{n+1}^{'} \qquad (2.8)$$

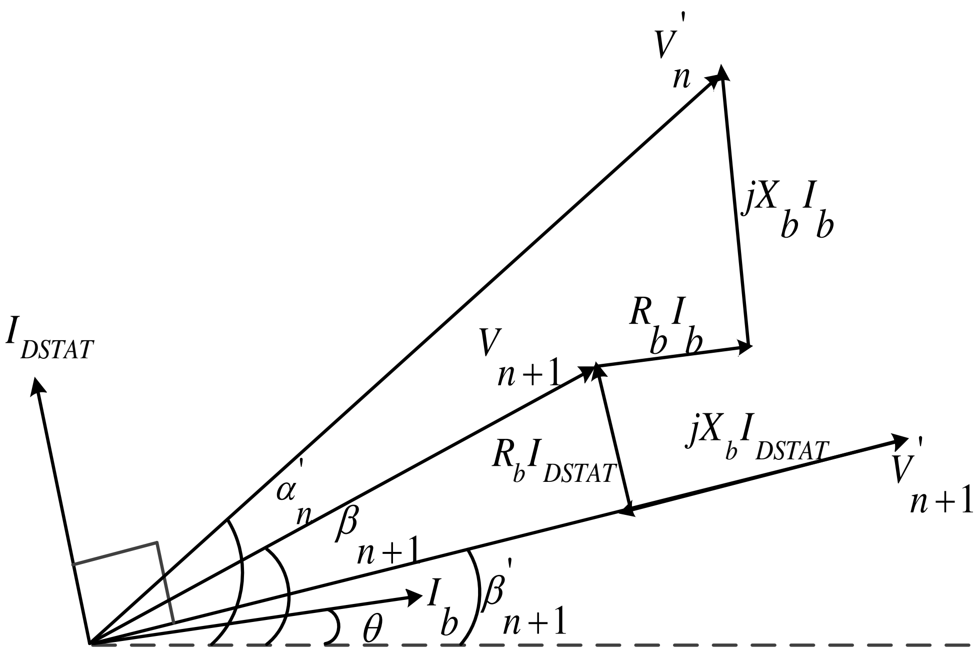

Figure.2.8: Phasor diagram for the network shown in Fig.2.7

The real and imaginary parts of Eq. (2.7) are separated and are computed as Eqs. (2.9) and (2.10).

Real Part:

$$\bar{I}_{DSTAT}\cos\left(\beta_{n+1}'+90°\right)=\left[\frac{\bar{V}_n' R_b\cos\alpha_n'}{R_b^2+X_b^2}+\frac{\bar{V}_n' X_b\sin\alpha_n'}{R_b^2+X_b^2}-\frac{\bar{V}_{n+1}' R_b\cos\beta_{n+1}'}{R_b^2+X_b^2}-\frac{\bar{V}_{n+1}' X_b\sin\beta_{n+1}'}{R_b^2+X_b^2}-\bar{I}_b\cos\theta\right] \tag{2.9}$$

Imaginary Part:

$$j\left(\bar{I}_{DSTAT}\sin\left(\beta_{n+1}'+90°\right)\right)=\left[\frac{\bar{V}_n' R_b\sin\alpha_n'}{R_b^2+X_b^2}+\frac{\bar{V}_n' X_b\cos\alpha_n'}{R_b^2+X_b^2}-\frac{\bar{V}_{n+1}' R_b\sin\beta_{n+1}'}{R_b^2+X_b^2}-\frac{\bar{V}_{n+1}' X_b\cos\beta_{n+1}'}{R_b^2+X_b^2}-\bar{I}_b\sin\theta\right] \tag{2.10}$$

Let,

$$a = -\frac{\overline{V}'_{n+1} R_b}{R_b^2 + X_b^2}, b = \frac{\overline{V}'_{n+1} X_b}{R_b^2 + X_b^2}, c = \frac{\overline{V}'_n R_b}{R_b^2 + X_b^2}, d = \frac{\overline{V}'_n X_b}{R_b^2 + X_b^2}, e = \overline{I}_{DSTAT},$$

$$\psi = \beta'_{n+1} + 90°,\ and\ \phi = \overline{I}_b$$

By replacing these parameters in Eqs. (2.9) and (2.10), the magnitude of the injected current of DSTATCOM has obtained as:

$$\overline{I}_{DSTAT} = \frac{K_1 + K_2 \sin\left(\alpha'_n - \theta - \varphi\right)}{\sin\left(\psi + \theta\right)} \tag{2.11}$$

Where, $K_1 = a\sin\left(\beta'_{n+1} + \theta\right) + b\cos\left(\beta'_{n+1} - \theta\right)$, $K_2 = \sqrt{c^2 + d^2} = \frac{\overline{V}'_n}{\sqrt{R_b^2 + X_b^2}}$,

"φ" is a unique angle satisfying the following conditions:

$i) -\pi < \varphi < \pi,$

$ii) tan\ \varphi = \frac{d}{c} = \frac{X_b}{R_b}, Since\ d \neq 0, c \neq 0$

Finally, Eq. (2.11) is the current which must be injected at a required n+1th bus of DN to compensate the reactive power to reduce the power loss. Hence the reactive power that can be provided by the DSTATCOM is expressed as follows:

$$jQ_{DSTAT} = \overline{V}'_{n+1} . I^*_{DSTAT} \tag{2.12}$$

The symbol '*' in Eq. (2.12) designates the complex conjugate. Eq. (2.12) is integrated into the load flow algorithm through the DEA to compute the load flow parameters voltage magnitude of each bus and the total power loss of the network. There are certain variables K_1, K_2, α'_n, β'_{n+1}, θ, φ, and ψ In Eq. (2.11). These variables decide I_{DSTAT}, and the value of I_{DSTAT} gets varied if the location of DSTATCOM is changed. Since the phase angle (β'_{i+1}) injection by DSTATCOM in node n+1 of RDS impacts the power loss to be reduced optimally, the phase angle (β'_{i+1}) injected in that node has been considered as an optimal variable. All the variables, except the optimal variable phase angle 'β'_{i+1}' are evaluated by the forward-backward sweep (FBS) load flow algorithm provided in next section.

However, for the very first iteration of the operation of FBS load flow algorithm, initially, a constant voltage of all nodes is assumed to be 1 p.u.∠0. The phase angle 'β'_{i+1}' selected by DE algorithm is injected into the reactive power load of the bus data of RDS in each iteration of the FBS load flow algorithm [99].

2.4. Incorporation of phase angle model of DSTATCOM in FBS algorithm

In the proposed approach, the best location and size of the DSTATCOM in RDS at different load levels have been found using the differential evolution optimization technique when the FBS algorithm is integrated in DEA. The DEA is worthless in the proposed approach without FBS algorithm. Line currents, bus voltages and power loss of RDS in each generation of DEA have been evaluated by FBS algorithm only when the size of the DSTATCOM is incorporated in FBS load flow algorithm through the data of RDS. Before discussing how the new phase angle model of DSTATCOM is incorporated in FBS load flow algorithm in the proposed approach, it is necessary to discuss how the FBS load flow technique works.

2.4.1. FBS Load flow technique

The proposed FBS load flow technique works based on to stages of evaluation, first stage is backward sweep and second stage is forward sweep. In first stage, all load and line currents are calculated and in second stage, all node voltages are determined using the results of first stage, these two stages depend on each other to perform the load flow calculations. Before these stages are started, initially each node voltage is assumed to be constant 1 p.u.∠0º. At the end of second stage, convergence condition is checked. If the convergence condition is not satisfied, then again first stage calculations are done using the most recent results of second stage, and this process reappears till the convergence condition is satisfied. The convergence condition is set as the value $1X10^{-3}$ p.u. is greater than the maximum voltage magnitude difference in the successive iterations. This operation of FBS load flow technique in RDS is discussed below.

First of all, a simple RDS has been considered as shown in Fig. 2.9 for the application of FBS load flow technique. As it can be seen in Fig. 2.9 that all node voltages are assumed as 1 p.u.∠0º. The loads at each node are represented by $S_{1\text{-}load}$ $S_{2\text{-}load}$ $S_{3\text{-}load}$ and $S_{4\text{-}load}$ respectively, and I_{12}, I_{23}, and I_{34} are the line currents and I_1, I_2, and I_3 are the load currents and I_S is the source current and Z_{12}, Z_{23}, and Z_{34} are the line impedances of the RDS.

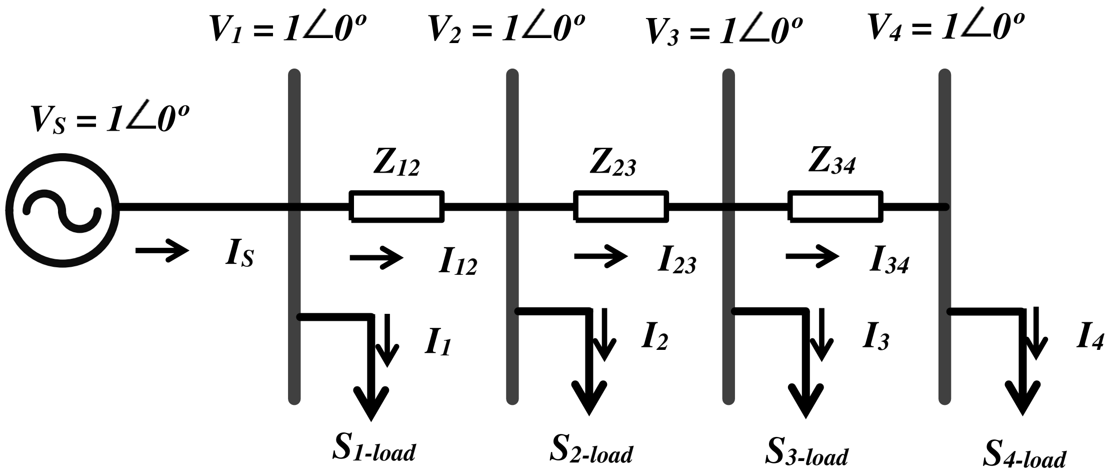

Figure.2.9: Simple RDS considered for FBS load flow studies

a) Backward Sweep operation

As discussed above in this operation the line currents of RDS are evaluated. Initially, the load current are calculated as shown in below Eqs. (2.13) to (2.16).

$$I_1 = \left(\frac{S_1}{V_1}\right)^* = \left(\frac{P_1 + jQ_1}{V_1}\right)^* = \left(\frac{P_1 - jQ_1}{1\angle 0^\circ}\right) \tag{2.13}$$

$$I_2 = \left(\frac{S_2}{V_2}\right)^* = \left(\frac{P_2 + jQ_2}{V_2}\right)^* = \left(\frac{P_2 - jQ_2}{1\angle 0^\circ}\right) \tag{2.14}$$

$$I_3 = \left(\frac{S_3}{V_3}\right)^* = \left(\frac{P_3 + jQ_3}{V_3}\right)^* = \left(\frac{P_3 - jQ_3}{1\angle 0^\circ}\right) \tag{2.15}$$

$$I_4 = \left(\frac{S_4}{V_4}\right)^* = \left(\frac{P_4 + jQ_4}{V_4}\right)^* = \left(\frac{P_4 - jQ_4}{1\angle 0^\circ}\right) \tag{2.16}$$

In above equations each value of active and reactive loads are taken from the data of RDS. Since this operation speaks about backward sweep, the line currents are calculated in backward direction from last bus using KCL applied at the buses 4, 3, and 2 and are expressed as given in Eqs. (2.17) to (2.20).

$$I_{34} = I_4 \tag{2.17}$$

$$I_{23} = I_{34} + I_3 \tag{2.18}$$

$$I_{12} = I_{23} + I_2 \tag{2.19}$$

$$I_S = I_{12} + I_1 \tag{2.20}$$

b) Backward Sweep operation

In this operation, the all bus voltages except the substation bus voltage 'V_1'of RDS are evaluated since the substation bus is referred as slack bus as discussed in 'section 1.1.8' of 'chapter 1'. Since this operation speaks about forward sweep the voltages are evaluated in forward direction from 'bus 2' using the equations expressed in Eqs. (2.21) to (2.23).

$$V_2 = V_1 - \left(I_{12} \times Z_{12}\right) \tag{2.21}$$

$$V_3 = V_2 - \left(I_{23} \times Z_{23}\right) \tag{2.22}$$

$$V_4 = V_3 - \left(I_{34} \times Z_{34}\right) \tag{2.23}$$

c) Convergence criteria

The convergence criteria is one which checks the accuracy of the values obtained in the operation of FBS load flow technique and checks it with the prespecified value set for the convergence condition. If the condition is satisfied, it stops the operation and display the results. To check the convergence the reference value of accuracy is set to a prespecified value 0.0001 *p.u.* in proposed approach. The evaluation of accuracy involves with the difference between the previous and present bus voltage obtained in iterative operations as shown below Eqs. (2.24) to (2.26).

$$\Delta V_2 = V_2^{old} - V_2^{new} \tag{2.24}$$

$$\Delta V_3 = V_3^{old} - V_3^{new} \tag{2.25}$$

$$\Delta V_4 = V_4^{old} - V_4^{new} \tag{2.26}$$

If the ΔV_2 or ΔV_3 or $\Delta V_4 \leq 0001$ then the FBS load flow gets stopped, or else the operations shall be repeated toll the convergence condition is satisfied.

Note: The load flow calculations are under per unit values.

2.4.2. Incorporation of a new phase angle model of DSTATCOM in FBS Load flow algorithm

The suitable new phase angle model of DSTATCOM devised in section 2.3 is incorporated in FBS load flow algorithm to achieve the objectives of the proposed approach. There exists an un known parameter 'β'_{n+1}' in the phase angle model of DSTATCOM as shown in Eq. (2.11) and is discussed in section 2.3. This parameter is considered as the optimal variable phase angle since it decides the amount of reactive power to be injected in RDS as shown in Eq. (2.12). Rest all variables in Eq. (2.11) are available from the FBS load flow algorithm results. However, to determine the optimal value of 'β'_{n+1}' and its location in RDS the DEA is used. The implementation of DEA in proposed approach is provided in coming chapters. How the amount of reactive power generated by DSTATCOM decided by 'β'_{n+1}' can be injected in RDS via FBS load flow technique is described in the following steps.

Step 1- *Backward Sweep:* In this step, the load current of each bus of DN having '*n*' number of buses is determined as follows:

$$\bar{S}_n = \bar{V}_n . \bar{I}^*_{Load_n} \tag{2.27}$$

The load current can be computed as:

$$\bar{I}_{Load_n} = \frac{P_{Load_n} - jQ_{Load_n}}{\bar{V}_n^*} \tag{2.28}$$

Where n= 1,….*m*, $P_{Load}(n)$ and, $Q_{Load}(n)$ are active and reactive power demand at the n^{th} bus. After the load current is determined then, branch currents of the network are computed by the following expression

$$\bar{I}_{b_{n,n+1}} = \bar{I}_{Load_{n+1}} + \sum_{n=1}^{m} \bar{I}_{Load_n} \tag{2.29}$$

The $n+1^{th}$ bus is the bus that appears after the n^{th} bus. To incorporate (integrate) the DSTATCOM say at $n+1^{th}$ bus, the demand for reactive power at that bus at which the DSTATCOM is allocated, is expressed by Eq. (2.30)

$$Q^{new}_{Load_{n+1}} = Q_{Load_{n+1}} - Q_{DSTAT_{n+1}} \tag{2.30}$$

In above Eq. (2.30), the value of Q_{DSTAT} is taken from Eq. (2.12).

Step 2- *Forward Sweep*: After the process of backward sweep algorithm forward sweep algorithm started to work to determine the voltage at each bus of DN as follows*:*

$$\overline{V}_{n+1} = \overline{V}_{n} - \overline{I}_{b_{n,n+1}} \overline{Z}_{b_{n,n+1}} \tag{2.31}$$

Where n+1 is the receiving end bus and, n is the sending end bus. $I_{bn,\ n+1}$ is the branch current between the buses n and n+1. $Z_{bn,\ n+1}$ is the impedance between the buses n and n+1.

Step 3- Convergence criteria: After the execution of above two steps during each iteration, the voltage mismatches at each bus is evaluated by

$$\Delta V_n^{(iter)} = \left| abs\left(V_n^{(iter)}\right) - abs\left(V_n^{(iter-1)}\right) \right| \tag{2.32}$$

If $\Delta V_n^{(iter)} < accuracy$ (2.33)

The *steps* 1 and 2 are repeated until convergence is achieved. Where, *iter* is the iteration number and *accuracy* is 0.0001.

The algorithm of FBS load flow technique used in the MAT-Lab simulation coding is described step by step is as follows in Table. 2.1. Also the flow chart of FBS load flow technique is shown in the Fig. 2.10

Table 2.1: FBS load flow algorithm

Step 1: Initialize accuracy for convergence criteria; Maximum iterations (max iter); and number of nodes (N);

Step 2: Assume all node voltages as constant, i.e., 1 p.u.∠0

Step 3: Read the bus data and line data which has the data of active and reactive power load at each node, and each line resistance and reactance of 69-node RDS

Step 4: Create dummy matrics with required sizes to store the values of node voltages, line currents, and power loss during the operation of algorithm

Step 5: Incorporate the DSTATCOM at j^{th} node as shown in the following Eq. (2.34)

$$\text{Reactive power load}_j^{new} = \text{Reactive power load}_j - \text{Reactive power load}_j^{DSTATCOM} \quad (2.34)$$

Where, $\text{Reactive power load}_j^{DSTATCOM} = jQ_{DSTATCOM}$ which is given in Eq. (2.12).

Step 6: Perform the operation of backward sweep to evaluate the line currents with the help of following Eqs. (2.35), (2.36), and (2.37)

$$\text{Apparent power load}_j^{new} = \text{Voltage}_j \times \text{Load current}_j^* \quad (2.35)$$

$$\text{Load current}_j = \frac{\text{Active power load}_j - j\,\text{Reactive power load}_j}{\text{Voltage}_j^*} \quad (2.36)$$

$$\text{Line current}_{ij} = \text{Load current}_i + \sum_{i=1}^{N} \text{Load current}_j \quad (2.37)$$

Step 7: Perform the operation of forward sweep to evaluate the node voltages using the following Eq. (2.38).

$$\text{Voltage}_j = \text{Voltage}_i - \text{Line current}_{ij} \times \text{Line Impedance}_{ij} \quad (2.38)$$

Step 8: Check the convergence criteria using the following Eqs. (2.39) and (2.40)

$$\Delta\text{Voltage}_i^{(k)} = \left| abs\left(\text{Voltage}_i^{(k)}\right) - abs\left(\text{Voltage}_i^{(k-1)}\right)\right| \quad (2.39)$$

$$\text{If } \Delta\text{Voltage}_i^{(k)} < accuracy \quad (2.40)$$

Step 9: Evaluate power loss (according to the power loss formulation in next chapter)

Step 10: If convergence criteria are not satisfied repeat from Step 5 to 9 until it gets satisfied

Step 11: End the program after convergence criteria are satisfied

Step 12: Print load flow results such as line current, node voltages, and the power loss

Note: Max Iter = 100, N = 69, accuracy = 0.00001, k = iteration count, i = Node number which appears before j^{th} node, j = Node number where the DSTATCOM is placed

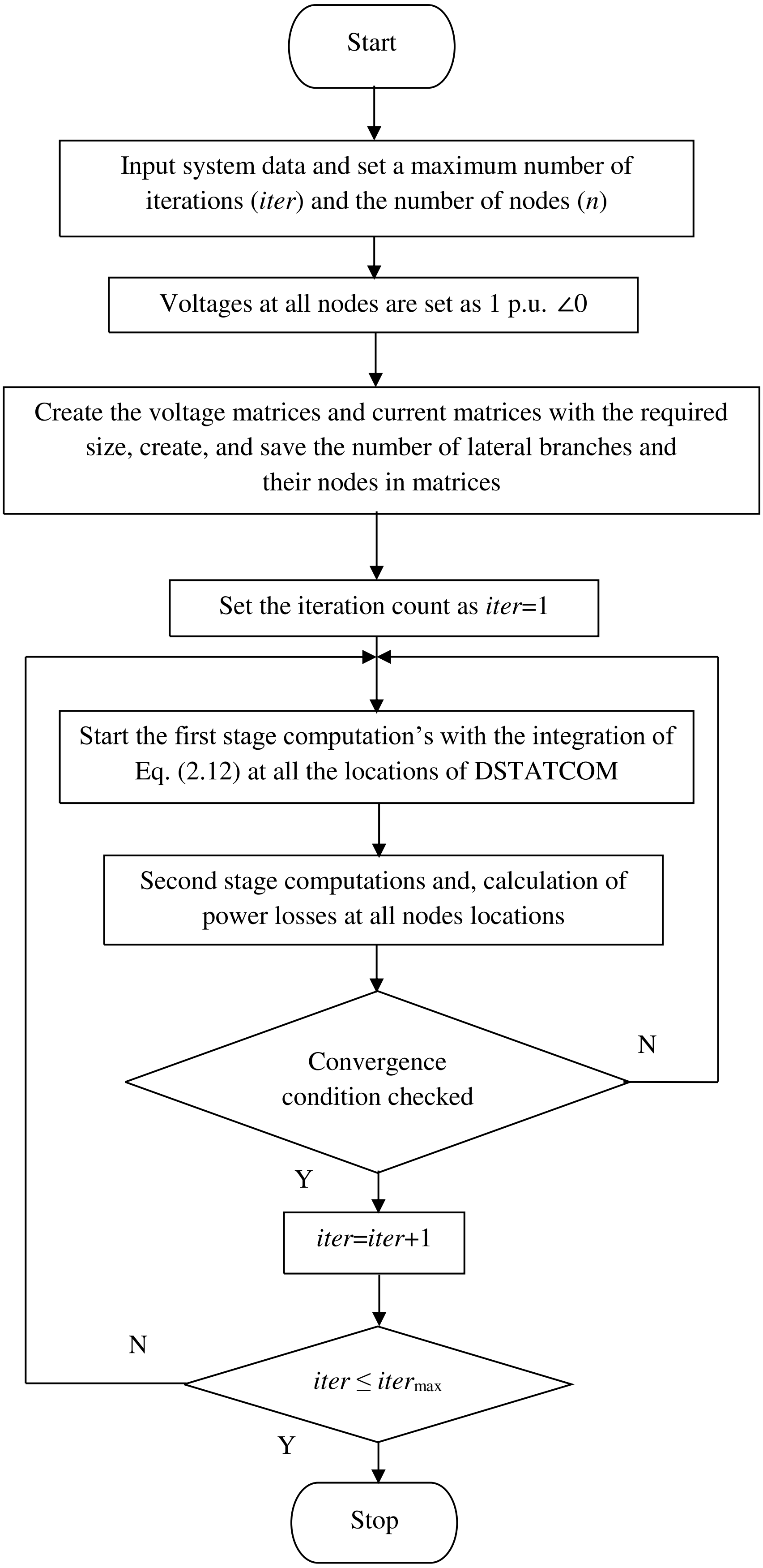

Fig. 2.10: Forward backward sweep algorithm flow chart integrating the DSTATCOM mathematical model

2.5. Conclusion

The essence of this chapter is devising a new phase angle model of DSTATCOM and incorporating it in RDS to compensate the reactive power in the RDS. To understand the modeling of DSTATCOM this chapter describes why DSTATCOM is required in RDS and how it works to compensate the reactive power in RDS. The FBS load flow technique is described clearly and its algorithm and flow chart are provided in this chapter. Mainly, how the phase angle model of DSTATCOM can be injected in RDS via FBS load flow algorithm is described elaborately in this chapter. This model is used in next all chapters to solve the objectives the thesis.

Chapter 3

Reactive Power Compensation in Radial Distribution Systems with the Optimal Phase Angle Injection Model of Single Distribution STATCOM

3.1. Introduction

In this chapter, a distribution STATCOM (DSTATCOM) model based on optimal angle injection is allocated optimally in RDS to compensate the reactive power. A DSTATCOM is allocated at each bus of a distribution system, one at a time, and its impact on system power loss and voltage profile are investigated. In the proposed DSTATCOM model, the rating of the DSTATCOM is determined with the injection of optimal phase angle of the voltage at the location, in which a DSTATCOM is placed. The proposed DSTATCOM model is suitably incorporated in the forward-backward sweep load flow algorithm as discussed in chapter 2. The optimal location and rating for DSTATCOM are determined by minimizing the active power loss of a distribution network. Exhaustive search and differential evolution algorithms are used as the solution strategy. The 30 and 69-bus radial distribution system is used in the case study. The results show that the proposed approach is more efficient in active power loss reduction as compared to some of the previously published approaches.

3.2. Optimal allocation of DSTATCOM in RDS using exhaustive search algorithm

In this section, the optimal allocation of proposed phase angle model of DSTATCOM in two different 30 and 69-bus RDS using exhaustive search method is presented. Firstly, the objective function is formulated required in the approach proposed in this chapter. Secondly, the operation of exhaustive search algorithm in proposed approach is described. The incorporation of DSTATCOM in FBS load flow algorithm discussed in chapter 2 is the main strategy to evaluate the load flow studies in this approach.

3.2.1. Objective Function

The placement of DSTATCOM is carried out to provide optimal reactive power compensation by considering the operational constraints of the network. The modelling of the DSTATCOM which is derived in chapter 2 is used to determine the optimizing variables, such as optimal location(s) for DSTATCOM and the corresponding angle β'_{i+1} so as to get the lowest total active power loss as given below.

$$P_{loss}^{DSTAT} = \sum_{j=1}^{n-1} I_{Brach}^{2}(j) \times R(j) \tag{3.1}$$

Where $I_{Branch}(j)$ and $R(j)$ represent the branch/line current and the resistance of the branch j, n is total number of buses in the RDS. This objective function is to be minimized under the following constraints:

3.2.1.1.Voltage constraint

Voltage at each bus must be remained within the permissible range.

$$V_i^{min} \leq V_i \leq V_i^{\max} \tag{3.2}$$

Where V_i is the magnitude of the voltage at bus number i, V_i^{min} min and V_i^{max} are the minimum and maximum limits of the voltage at bus number i. Minimum voltage is taken as 0.9 pu and maximum voltage limit is take as 1.05. If the voltage at bus i cross these limits a penalty factor is added with the objective function given in Eq. (3.1)

3.2.1.2.Thermal constraint

The current flowing through each branch must be within maximum current carrying capacity of the conductor.

$$I_j \leq I_j^{\max} \tag{3.3}$$

Where I_j is the magnitude of the current flowing through the branch j and I_j^{max} is the maximum limit of the current in the branch j. Maximum limit of the current is taken as 1.2 times the base current of the branch j. If the voltage and current of any bus or branch violates these constraints, a penalty factor is added with the objective function in Eq. (3.1). Hard constraints principle is used in this chapter.

3.2.2. Exhaustive search optimization method (ESM)

Exhaustive search technique is a general problem solving technique, which enumerates each possible candidate systematically for the problem solution while keeping a check whether each candidate solution is satisfying the statement of the problem or not [109]. Generally, this technique is used in discrete problems since these problems have no other efficient techniques. However, the proposed problem has many techniques to solve. This method can also be called as brute force method or direct search method or generate and test method or British museum algorithm. Exhaustive search has two requirements that it should be able to generate all candidate solutions and to check a candidate solution [110]. Also, generating and checking candidates should be efficient. A generalized pseudocode for the exhaustive search method (ESM) is given in Table. 3.1 and ESM algorithm for the proposed approach is given is Table. 3.2. ESM algorithm has the following advantages:

1) Its operation is simple
2) It can reduce the search space
3) It allows randomization so that the runtime gets improved
4) It is widely applicable, particularly to search-oriented problems
5) It is correct search method and gives correct generation and checking

Table.3.1: A generalized pseudocode for the exhaustive search algorithm:

```
Joseph (int NIT, int RKL)
{
  If (is solution (NIT))
    Print solution (NIT)
  Else {
    NIT generated = generate solution ( )
    Joseph (NIT generated, RKL+1)
  }
}
```

Table.3.2: ESM Algorithm for proposed approach:

Require: Initialization of accuracy; maxiter; no. of nodes;

Require: Read the bus data and line data

Require: Create dummy matrices mat, V, X, and Rosh with required sizes in zeros/ones

```
for location=1:n
   for cap=1:1:pahse angle or specified maximum limit of QDSTATCOM rating
      for iter=1:maxiter
         for j=n:-1:2
           Ij=conj (complex(s (j, 1), s (j, 2)-QDSTATCOM)/V (1, j));
              while (j<=n)
                count=0;
                if (count==1)
                end node = j;
                elseif (count==2)
             end
             break
         end
     end
if (max (abs (DIF))<=accuracy)  %( check convergence)%
break
end
end
P loss /Q loss =0;
for b=1:n-1
   Evaluate (P loss /Q loss)
end
Rosh (location, cap) = P loss /Q loss;
end
end
Print size of DSTATCOM; Plot minimum P loss /Q loss and voltage;
```

3.2.3. 69-bus RDS

Optimal allocation of phase angle model of DSTATCOM in 12.66kV, 100MVA, 69-bus RDS [68] and [103] using exhaustive search algorithm is presented in this section.

3.2.3.1. DSTATCOM allocation strategy

In the modelling of the DSTATCOM derived in chapter 2 there is an unknown parameter, i.e., the angle β' .This is the angular displacement of the voltage at the location where a DSTATCOM is placed. This angle can vary between the limits 0 to 90 degrees. In this work, three different values of β' are chosen to design to determine the current to be injected by a DSTATCOM. They are:

- Case A: Design of DSTATCOM with β'=18.4°
- Case B: Design of DSTATCOM with β'=32.1°
- Case C: Design of DSTATCOM with β'=68.4°

The respective reactive power to be injected by the DSTATCOM is obtained from Eq. (2.12), chapter 2. In this work, a DSTATCOM is placed at each bus of the RDS one at time and the system power loss is computed by incorporating the proposed model in the forward-backward sweep load flow algorithm.

Initially, a constant voltage of all buses is assumed to be 1 p.u.$\angle 0$. Then, load currents that are connected at all buses are calculated and line currents are determined by using in backward sweeps. Thereafter, the voltage at each bus is computed in forward sweeps. Once the new voltages at all buses are computed, the convergence criterion is checked. If it does not converge, then load currents are evaluated using the most recent values of voltages and the whole process is repeated till the convergence criterion is satisfied. The convergence criterion is set as the maximum difference in magnitude of voltages in the consecutive iterations is less than 1X10^{-3} p.u.

3.2.3.2.Simulation Result

In this section, the results of the computer simulation study are given to show the impact of the allocation of phase angle model of DSTATCOM on RDS. The base case power loss of the 69-bus RDS is 224.98 kW.

A. Impact of DSTATCOM Allocation on Network Loss

To study the impact of the DSTATCOM, it is placed in each bus, one at a time and the power loss due to the DSTATCOM allocation is shown in Fig. 3.1. It is observed that there is significant reduction in power loss at certain buses, for example at buses 11-20 and buses 52-61. The DSTATCOM location corresponding to the minimum power loss is found to be bus 61. Thus, the voltage profile of the network with and without DSTATCOM allocation at bus 61 is shown in Fig. 3.2. It is also observed that both power loss and voltage profile are improved with a DSTATCOM designed with higher β'. Hence, better results are found in Case C design of DSTATCOM. The power loss and percentage reduction in power loss due to the DSTATCOM allocation at bus 61 are given in Table 3.1.

Table 3.3: Results obtained with DSTATCOM allocation at bus 61

Location	**Case**	**β' (deg)**	**MVA rating**	**Power Loss (kW)**	**Power Loss reduction (%)**
61	Case A	8.4°	0.931	159.04	29.3%
	Case B	32.1°	0.958	157.77	29.8%
	Case C	68.4°	0.969	155.63	30.8%

B. Analysis of the VA rating of DSTATCOM

The VA rating for the DSTATCOM placed in different locations of the 69 bus test system, one at a time is shown in Fig. 3.3. The results illustrate that higher-rated DSTATCOM is required if it is to be placed closer to the substation. It is expected because the branches located closer to the substation carry higher load current. It is also observed that increase in angle of β' causes the requirement of a higher amount of shunt compensating current in the compensation of reactive power. This is the reason of higher VA rating of the DSTATCOM in planning Case C as shown in Table 3.1. Installation of DSTATCOM by the proposed approach leads to 30.8% of power loss reduction in the 69-bus RDS. The load flow results shows that power loss and voltage profile can be significantly improved due to a DSTATCOM allocation.

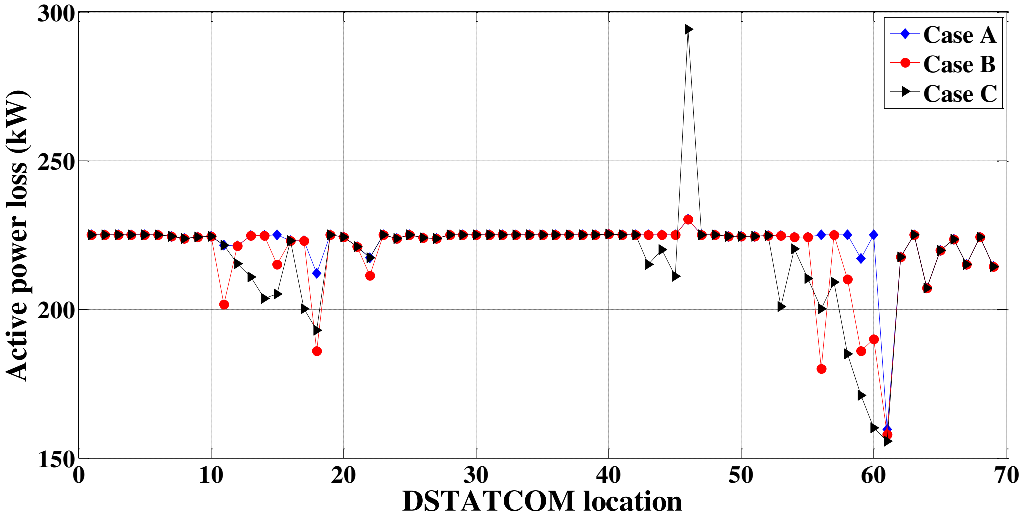

Figure.3.1: Active power loss after installation of DSTATCOM in RDS

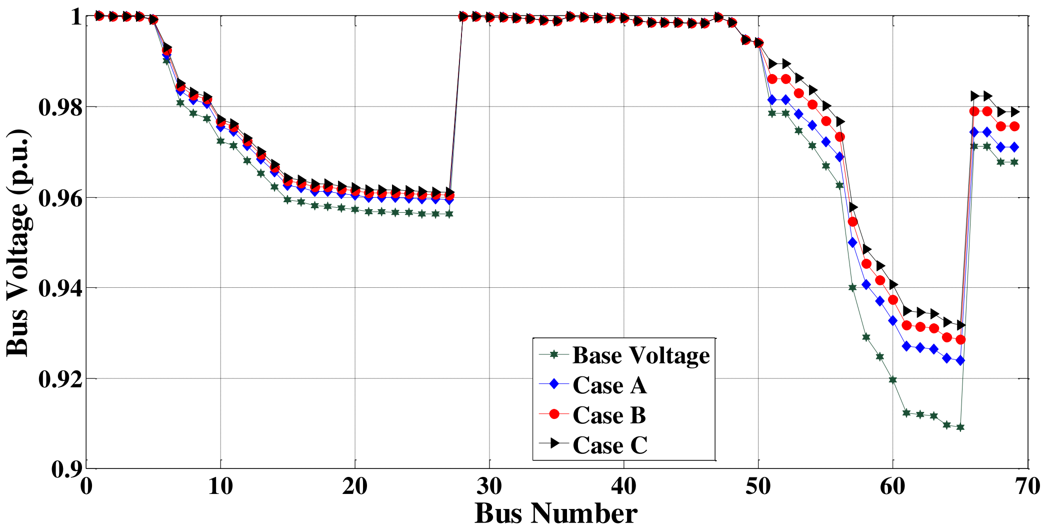

Figure.3.2: Voltage magnitude in different cases with DSTATCOM at bus 61

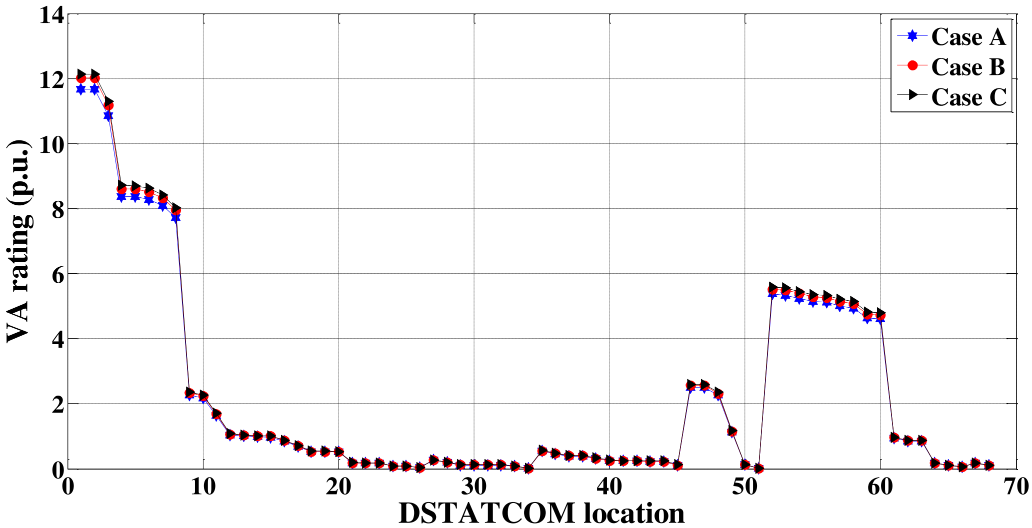

Figure.3.3: VA rating required for DSTATCOM in different locations of RDS

3.2.4. 30-bus RDS

Optimal allocation of phase angle model of DSTATCOM in 11kV, 100MVA, 30-bus RDS [89] using exhaustive search algorithm is presented in this section.

3.2.4.1.DSTATCOM placement scheme

In this work, the size of the DSTATCOM Q_{DSTAT} as shown in Eq. (2.12) in chapter 2 is varied between the '1kVAr' to '2000kVAr' to determine the maximum possible reduction in power loss. The Eq. (2.12) compensates the reactive power to minimize the power loss of RDS when it is injected into the certain nodes of RDS. The system power loss are computed by integrating the proposed DSTATCOM model in the forward-backward sweep load flow algorithm. The various size(s) of DSTATCOM between the ranges of 1 kVAr to 2000 kVAr are injected at each node one at a time to compute power loss and voltage magnitude.

3.2.4.2. Simulation Results

In this section, mat-lab simulation results are described to show that there is reduction in power loss and improvement of voltage profile after the DSTATCOM is placed in RDS using exhaustive search method. The system power loss of the base-case network is 147.05 kW when the accuracy of convergence condition is 0.0001.

Table 3.4: Results obtained with DSTATCOM allocation at node 5 using exhaustive search

Operational aspect	Power loss (kW)	Size (kVAr)	Minimum node voltage (p.u.)	Power loss reduction (%)
Without DSTATCOM	147.05	--	0.9046	--
With DSTATCOM at node-5	101.45	1161	0.9305	31.01

A. Reactive power compensation to reduce power loss

To find the maximum feasible reduction in power loss, the DSTATCOM of various sizes from 1 kVAr to 2000 kVAr are placed in incremental manner in each node except substation node, one at a time till the solution satisfies the network voltage and thermal constraints and the corresponding power loss is plotted in Fig. 3.4. Best size of DSTATCOM is found on the basis minimum power loss reduced. It is observed that in

Fig. 3.4 there exists a certain value of reactive power injected, in which power loss is minimum, and it starts increasing beyond the value. The size of the DSTATCOM corresponding to the minimum power loss, and the minimum node voltages due to DSTATCOM integration in all nodes are given in Fig. 3.5, 3.6, and 3.7 respectively. The results show that the minimum power loss is obtained at node 5 of IEEE-30 node RDN.

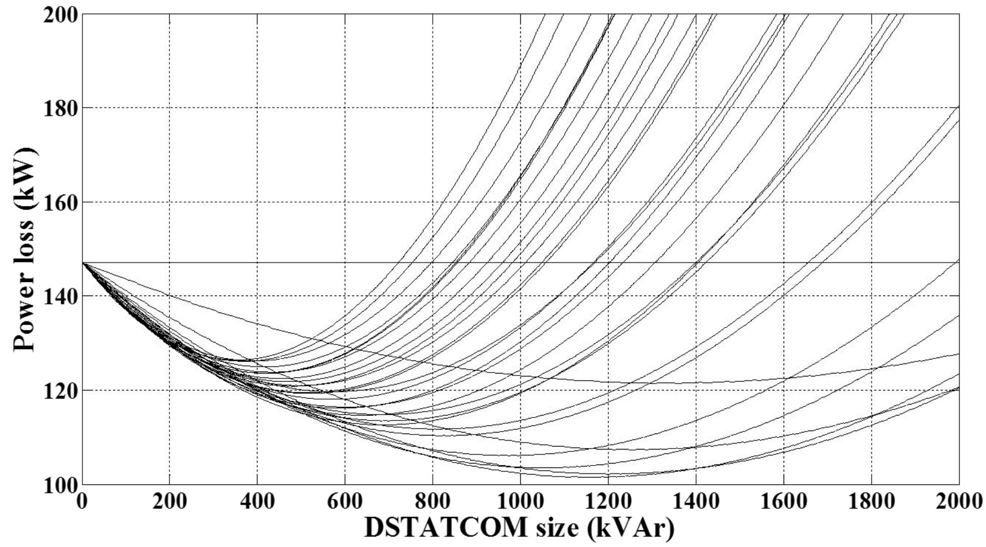

Figure.3.4: Variation of power loss with increment of DSTATCOM size in each node

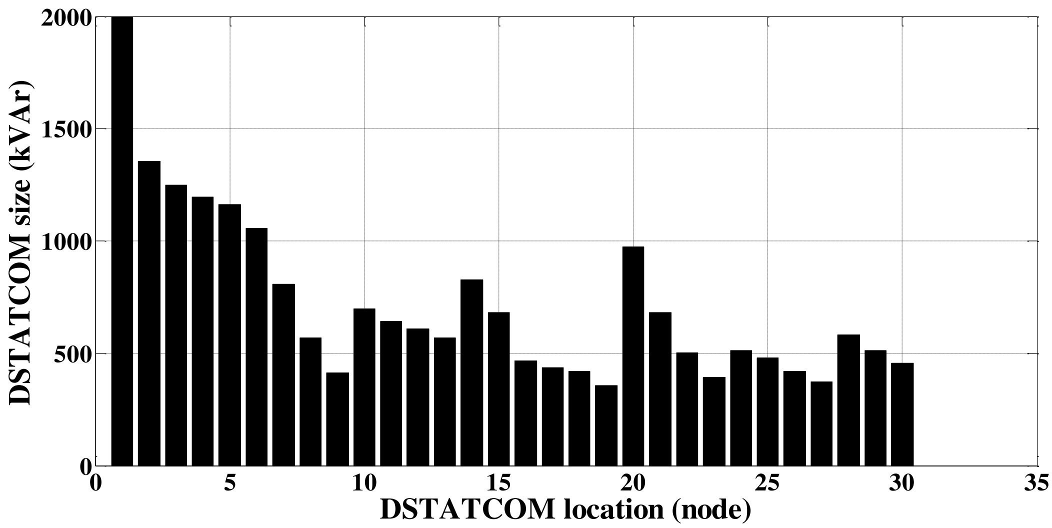

Figure.3.5: DSTATCOM size corresponding to minimum power loss

B. Analysis of the power loss and voltage profile

There is an apparent impact of DSTATCOM on the network power loss as shown Fig. 3.4 and 3.6. Network power loss significantly reduced at almost all nodes. Mainly at the nodes 3 to 7, 10 to 15, 20, 21, 28, and 30, power loss reduced between the range 19.75% to 31.01%. It is observed that the highest percentage reduction in power loss occurred at node 5 as 101.45 kW with the DSTATCOM size of 1161 kVAr as shown in Table.3.4. Moreover, it is noteworthy that voltage also improved significantly compared to base case voltage as shown in Fig. 3.8 after the placement of DTSTCOM at node 5. The improvement in minimum node voltage and reduction in power loss due to the impact of DSTATCOM placement at node 5 are provided in Table 3.4.

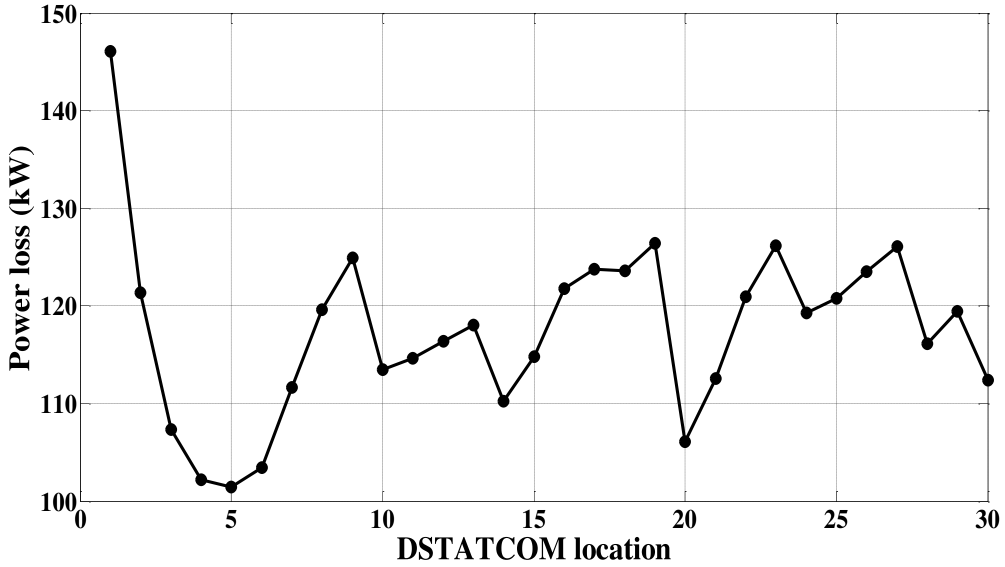

Figure.3.6: minimum power loss in each node due to integration of DSTATCOM

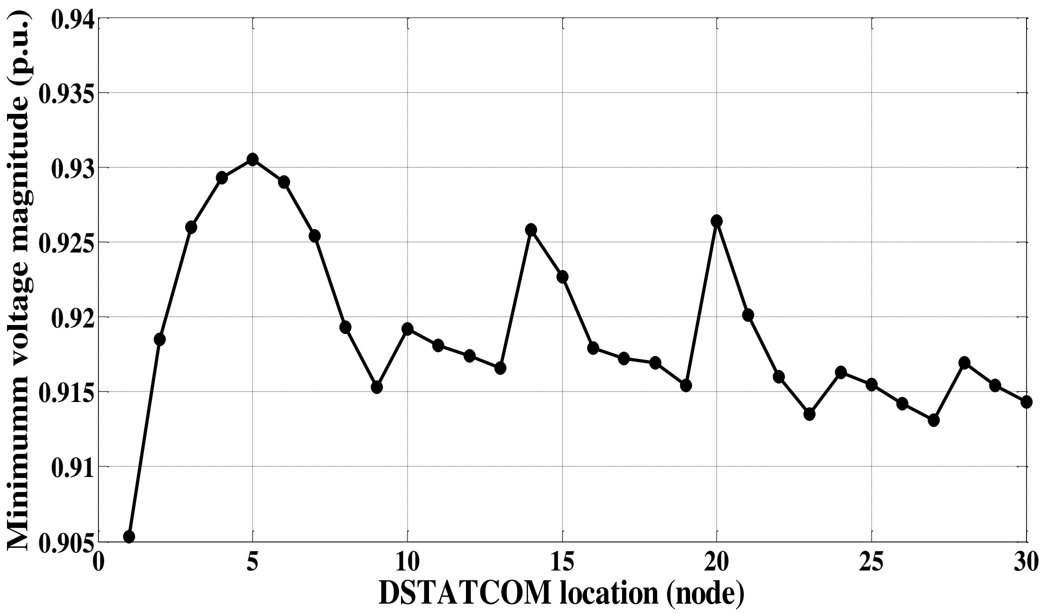

Figure.3.7: minimum node voltage due to the integration of DSTATCOM

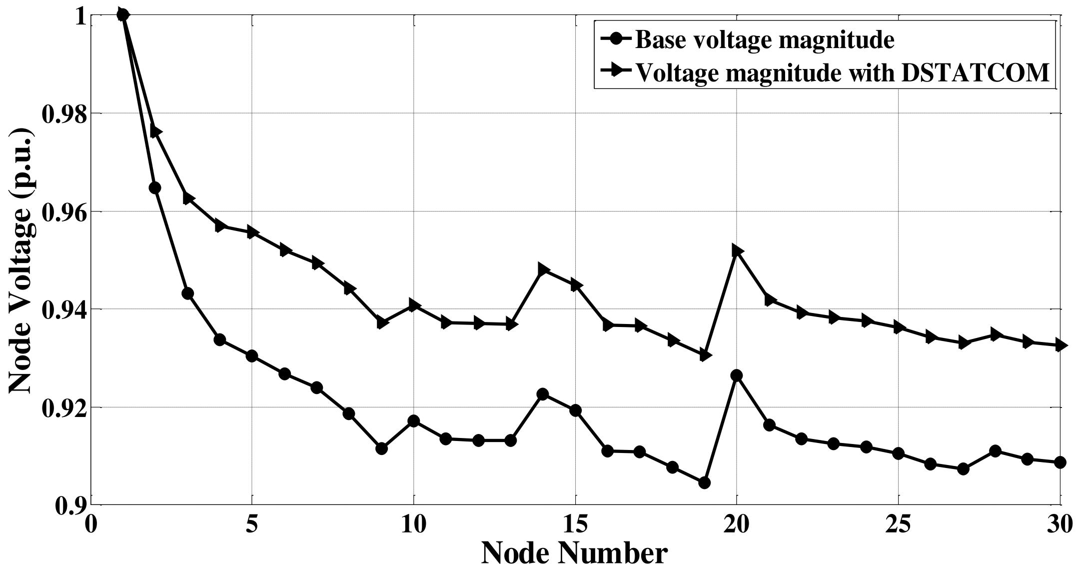

Figure.3.8: Voltage magnitude with DSTATCOM at node 5

C. Analysis of the size of DSTATCOM

The size (rating) of the DSTATCOM placed in different locations of the 30 node RDN, one at a time is shown in Fig. 3.5. This graph demonstrates that the size of DSTATCOM is to be higher when it is placed nearby substation. Generally the branches of the RDN which are near to substation carries higher load current and hence, it is estimated that the shunt current that must be injected for the compensation of reactive power is to be higher which consequently increases the size of the compensation device. Placement of DSTATCOM by the proposed approach leads to 31.01 % of power loss reduction in the IEEE-30 node RDN.

3.3. DSTATCOM Allocation Using DE

This section provides the objective function for the proposed planning problem for single DSTATCOM allocation and the detailed solution strategy using DE.

3.3.1. DE: an overview

In this subsection, a brief overview on DE [98] is provided. DE is an efficient population-based meta-heuristic search technique for solving problems of the global optimization by using the operator's mutation, crossover, and selection [99] - [101]. Firstly, the parameters of DE algorithm are initialized, and then the target vector is generated. Secondly, the mutant vector corresponding to each string of the target vector is produced by the operation of mutation. Thirdly, the trial vector is generated by performing the crossover operation between the target vector and its corresponding mutant vector. Fourthly, the trail vector is generated after that, an operation of selection is executed. The population consists of *Np* individual strings and each individual has a dimension *D* equals to the number of optimizing variables. The initial population generated is randomly generated under the limits of optimizing variables. The population in subsequent generations are evolved by the application of evolutionary operators, such as mutation, crossover, and selection till the termination criterion is satisfied. The evolutionary operators are briefly described below. The flow chart of DEA is shown in Fig. 3.9.

Step 1. Initialization: Number of strings as population Np, and the dimension (*D*) of optimization variables in each individual string, so called target vector (TG) are initialized and randomly generated by

$$TG_{i,Gen}^{j} = round\left(TG_{\min}^{j} + \left(\left(TG_{\max}^{j} - TG_{\min}^{j}\right).rand()\right)\right) \tag{3.4}$$

Where, $i = 1,2,\ldots,Np$; $j = 1, 2,\ldots,D$ and *Gen* is the generation number.

Step 2. Mutation: In each generation, for each target vector $TG^{j}_{i,Gen}$, a mutant vector $MUT_{i,Gen}$ is produced by the following equation:

$$MUT_{i,\,Gen} = TG_{best,\,Gen} + F.\left(TG_{r_1,\,Gen} - TG_{r_2,\,Gen}\right) \tag{3.5}$$

r_1, r_2 are individual integers that are generated randomly between the ranges [1, *N*p]. These integers are generated once for each mutant vector. The weighting factor *F* is a positive number for scaling the difference vector which is constant in the range 0 to 2. TG_{best} is the best target vector according to the objective (fitness) function value in the population at that particular generation *Gen*.

Step 3. Crossover: after the accomplishment of operation of mutation, the operation of crossover is required to be performed on each and every pair of the target vector $TG_{i,Gen}$ and its corresponding mutant vector $MUT_{i,Gen}$ for the generating a trial vector $CROS_{ji,Gen}$ using the following equation:

$$CROS_{ji,Gen} = \begin{cases} MUT_{ji,Gen} \text{ if } rand\ (\ ) \le CR \\ TG_{ji,Gen} \quad otherwise \end{cases} \tag{3.6}$$

where, *CR* is the cross over rate which is called as crossing factor and it is an user-defined parameter between range of [0, 1]. Crossing factor controls values that are available from the mutant vector.

Step 4. Selection: Selection is an operation which will be performed after the crossover. . Before this operation is performed, it is an important thing to be noted that, "If the values of string variables of a newly generated trial vector exceed the corresponding upper and lower limits, then these variables are reinitialized randomly within the pre specified limits. Then, the fitness function values of all trial vectors are computed. After that, a selection operation is performed. The fitness (objective) function value of each trial vector $f\,(CROS_{j\,i,\,Gen})$ is compared with the respective target vector $f\,(TG_{j\,i,\,Gen})$ in the current population. If the trial vector has less or equal fitness (objective) function value than the respective target vector, then the target vector will be replaced by the trial vector and entered the population of the coming generation. Otherwise, in the coming generation the target vector would be remained in the population. The operation of selection is as follows:

$$TG_{i,Gen+1} = \begin{cases} CROS_{i,Gen} \text{ if } f\,(CROS_{i,Gen}) \le f\,(TG_{i,Gen}) \\ TG_{i,Gen} \quad otherwise \end{cases} \tag{3.7}$$

Where f is the fitness function, i.e., the objective function shown in Eq. (3.1). The above steps, i.e., mutation, crossover and selection are repeated in each generation until the population is converged to an optimum value.

3.3.2. Proposed Solution Strategy Using DE

In the proposed scheme, a typical string for DE consists of the information of location for DSTATCOM and the phase angle β'_{i+1} (derived in chapter 2). All the busses except the substation bus are considered as candidate location for DSTATCOM and the range for the phase angle β'_{i+1} should lie in between 0 to 90 degrees.

3.3.3. Proposed DE algorithm

Algorithm:

Step 1: Initialize number of population=NP=50; size of the string=D=7; maximum generation=100; F= 0.5; CR= 0.6;

Step 2: Create dummy matrices to save the results of optimal location, optimal phase angle, and optimal power loss during the operation of Target vector (TG), Mutant vector (MUT) and trail vector (U).

Step 3: Initialize the lower limit (LT) and upper limit (UL) of optimal location and phase angle.

Step 4: Generate 'TG' (populations) with 50 strings in the format as shown in Fig.4.2 whose variables are randomly chosen according to the following equation

TG (POP, D) = round (LT+ ((UT-LT)* rand ()));

Step 5: Run the FBS load flow algorithm as described in "Algorithm" given in chapter 2 for each string of 'TG' and evaluate the power loss according to the Eq. (3.1)

Step 6: Generate 'MUT' (population) using the operation of mutation by mutating the variables in each string of 'TG' for '100' generations according to the following equation

MUT (POP, Variable) =abs (floor (TG (R0, Variable) +F*((TG (R1, Variable))-(T (R2, Variable)))));

Where R0 =ceil (NP*rand ()); while (R0=POP)
R1=ceil (NP*rand ()); while (R1=R0||R1=POP)
R2=ceil (NP*rand ()); while (R2=R1||R2=R0||R2=POP)
F= weighting factor

Step 7: Repeat step 5 for each string of 'MUT'

Step 8: Generate 'U' (population) using the operation of crossover for '100' generations according to the following statements

```
if ((rand()<=CR)||(D=Drand))
    U(POP,D)=MUT(POP,D);
else U(POP,D)=TG(POP,D);
end
```

Where Drand=ceil(1+(rand*3));
CR=Crossover Rate

Step 9: Repeat step 5 for each string of 'U'.

Step 10: Select the best (optimal) location, value of phase angle based on the best minimum power loss through the operation of 'selection' as given below

if (U_P_{loss}(POP) <= TG_P_{loss}(POP))

TG (POP, :) = U (pop, :);

else TG (POP, :) = T (POP, :);

end

Where U_P_{loss} = Power loss corresponding to each string of Trial vector (MUT)

TG_P_{loss} = Power loss corresponding to each string of Target vector (TG)

Step 11: End

Step 12: Print optimal result

3.4. Simulation Results

In this section, the simulation results are presented to show the impact of the allocations of single DSTATCOM in the network to minimize the active power loss. The active and reactive power loss of the base-case network is 224.98 kW and 102.1 kVAr respectively. The parameters of DE algorithm are optimized by taking repetitive runs and the optimal parameters are shown in Table 3.5. Firstly, the ESM algorithm is applied to know the optimal location and rating of DSTATCOM. In this method the optimal variable phase angle β'_{i+1} is injected in RDS through FBS from 0º to 90º in an incremental manner. The corresponding powerless to injection of each angle of β'_{i+1} have been recorded. Secondly, the DE algorithm is used to optimize the objectives of the proposed approach in this chapter.

Table 3.5: Parameters of DE algorithm

DE parameters	**Values**
Population size	50
Maximum Generation	100
Crossover rate	0.6
Weighting factor	0.5

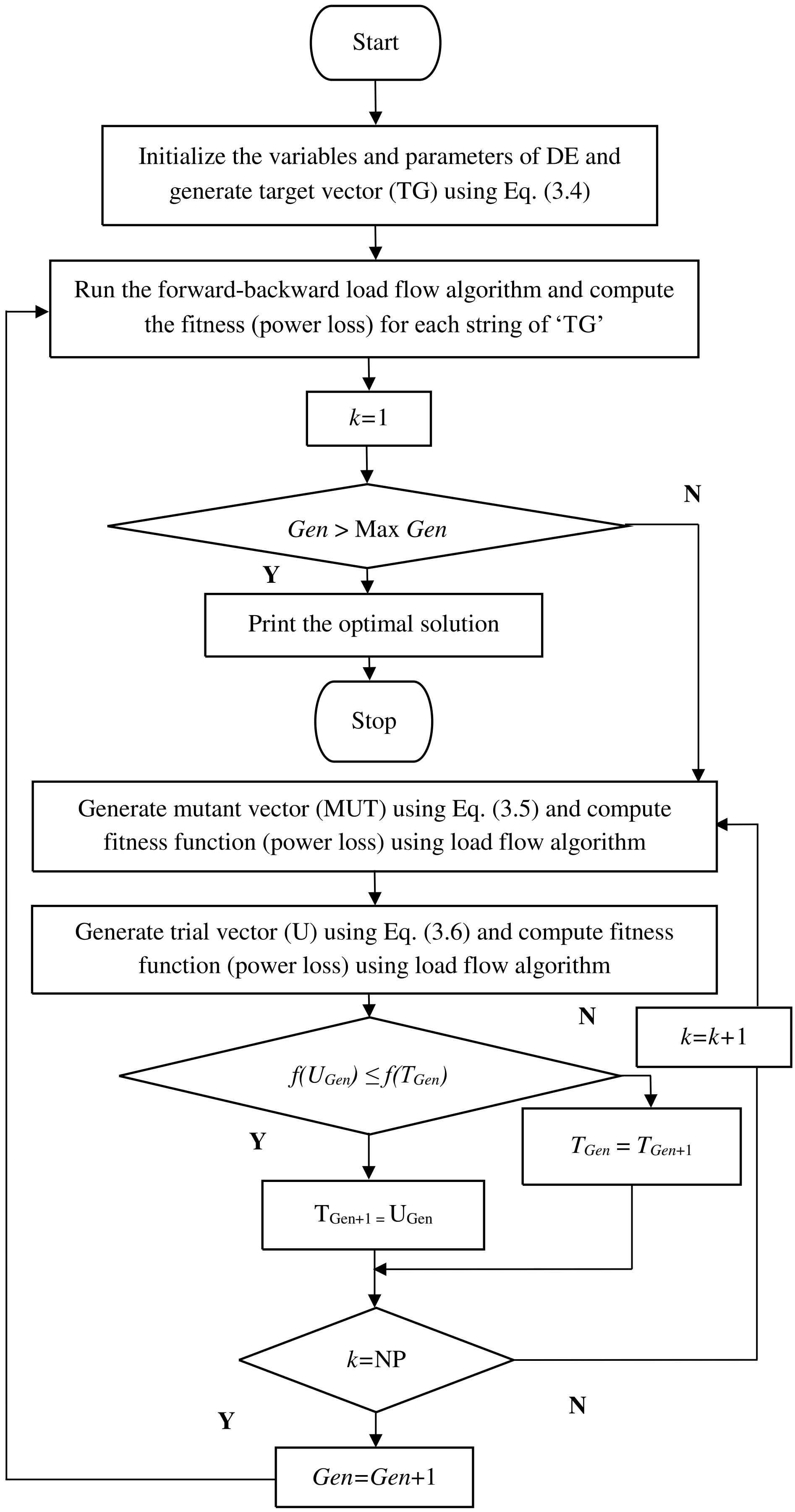

Figure.3.9: Flow chart of proposed DE algorithm

3.4.1. Results of Exhaustive Search

Firstly, an exhaustive search, in which a DSTATCOM is placed in each node, except the substation node, one at a time, is carried out. To determine the optimal DSTATCOM location and rating, the phase angle β'_{i+1} is varied from zero to 90 degree and the corresponding active power loss is plotted in Fig. 3.10. It is observed that the active power loss initially decreases with increase in phase angle β'_{i+1} and there exists a certain value of phase angle for DSTATCOM, in which the network active power loss is minimum and it starts increasing beyond the value. This shows the need of considering the phase angle β'_{i+1} as an optimizing variable.

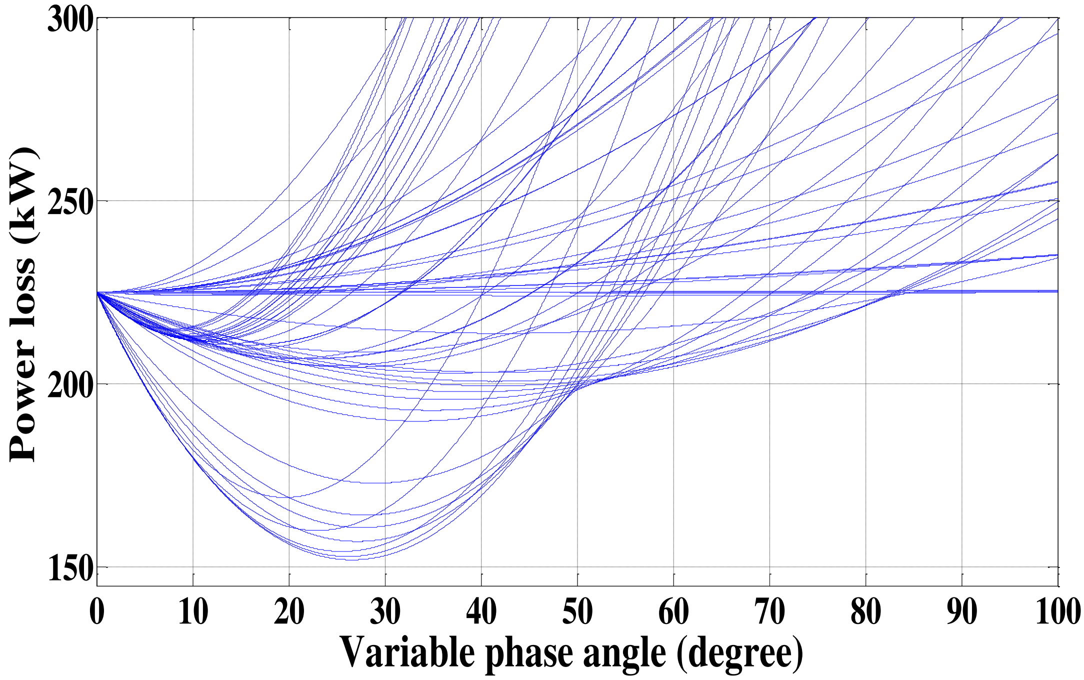

Figure.3.10: Variation of active power loss with increment of phase angle β'_{i+1} in each bus

The rating of DSTATCOM corresponding to the minimum active power loss, the value of minimum active power loss, the minimum bus voltages with DSTATCOM allocation in all buses and the value of minimum reactive power loss are given in Figs. 3.11, 3.12, 3.13, and 3.14 respectively. The phase angle corresponding to the minimum active power loss varies depending on DSTATCOM locations. In most of the locations, the variation lies between 20-30 degrees. The results show that the minimum active power loss can be obtained if a DSTATCOM is placed in bus 61.

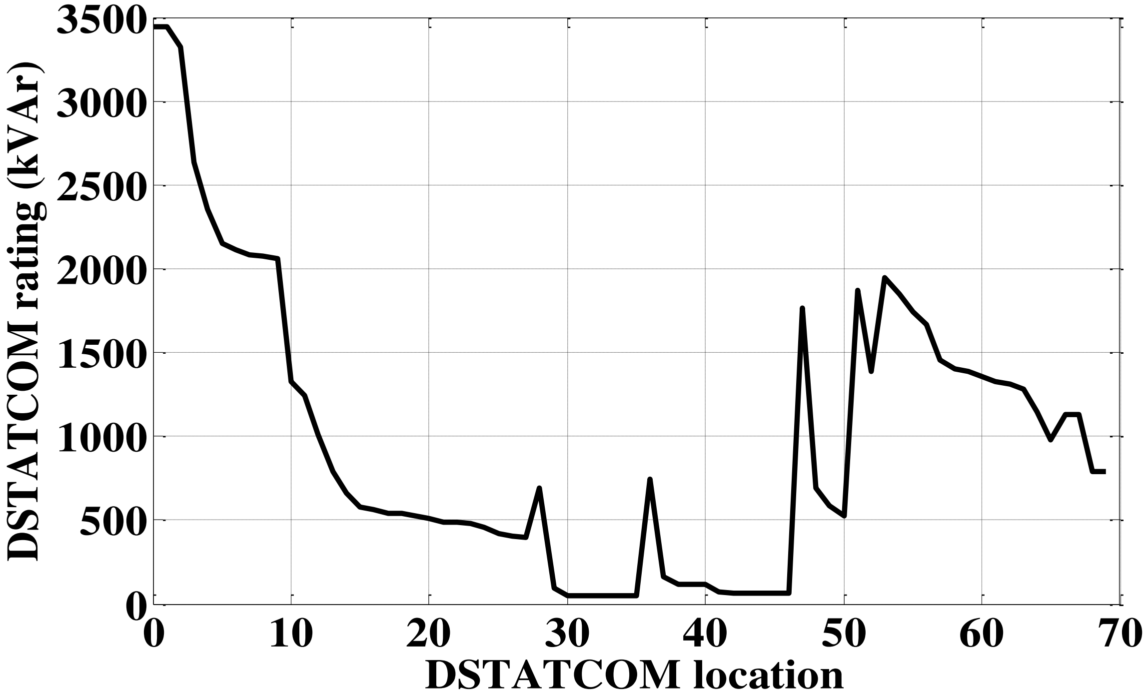

Figure.3.11: DSTATCOM rating in kVAr corresponding to minimum active and reactive power loss

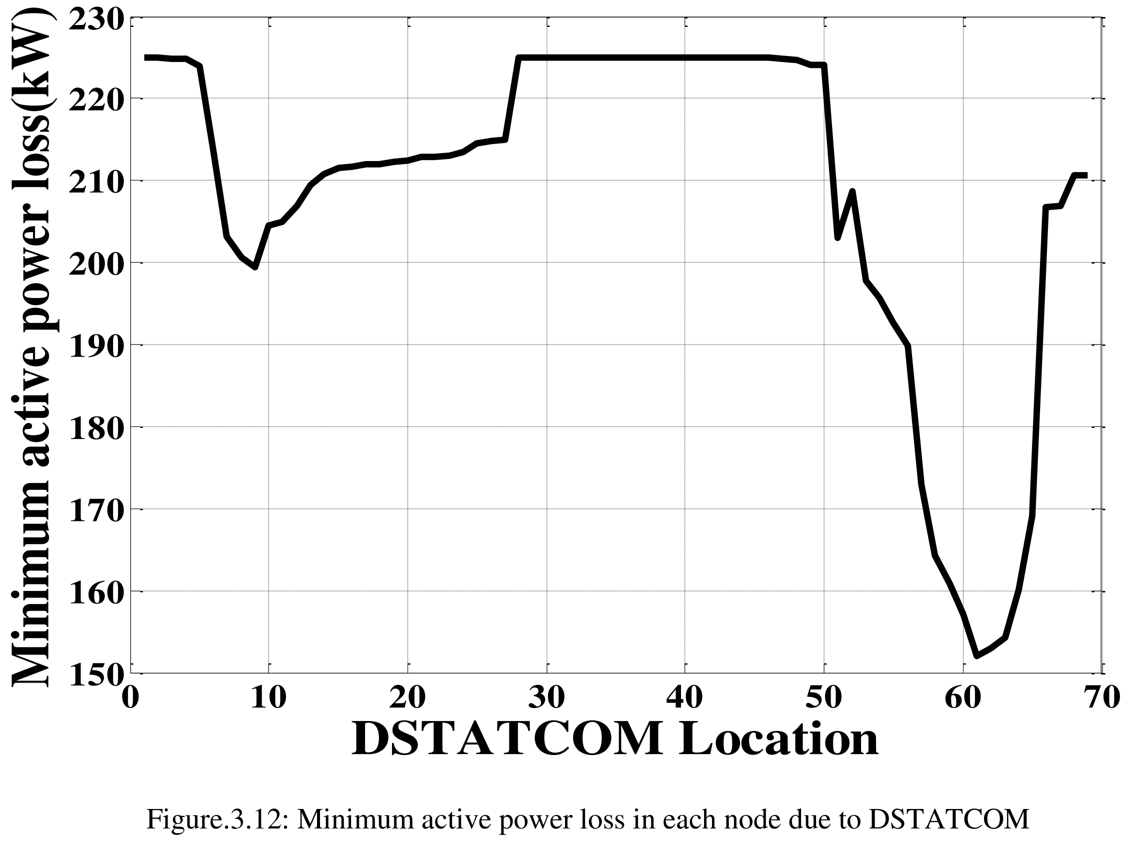

Figure.3.12: Minimum active power loss in each node due to DSTATCOM

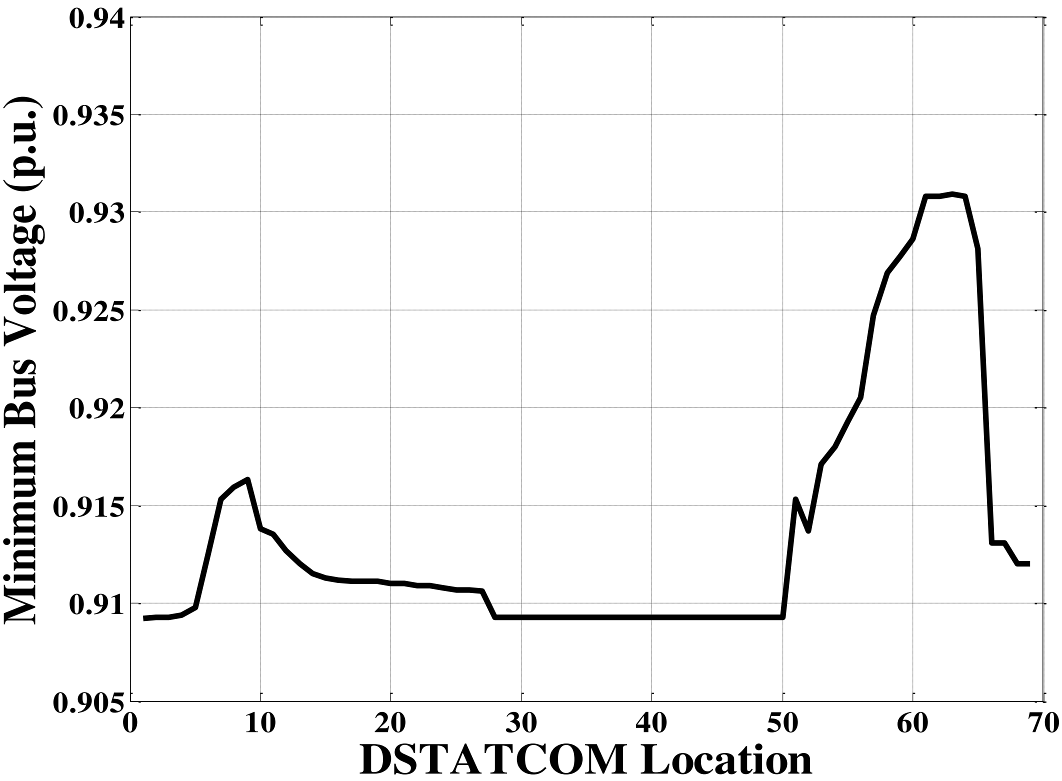

Figure.3.13: Minimum bus voltage due to DSTATCOM integration

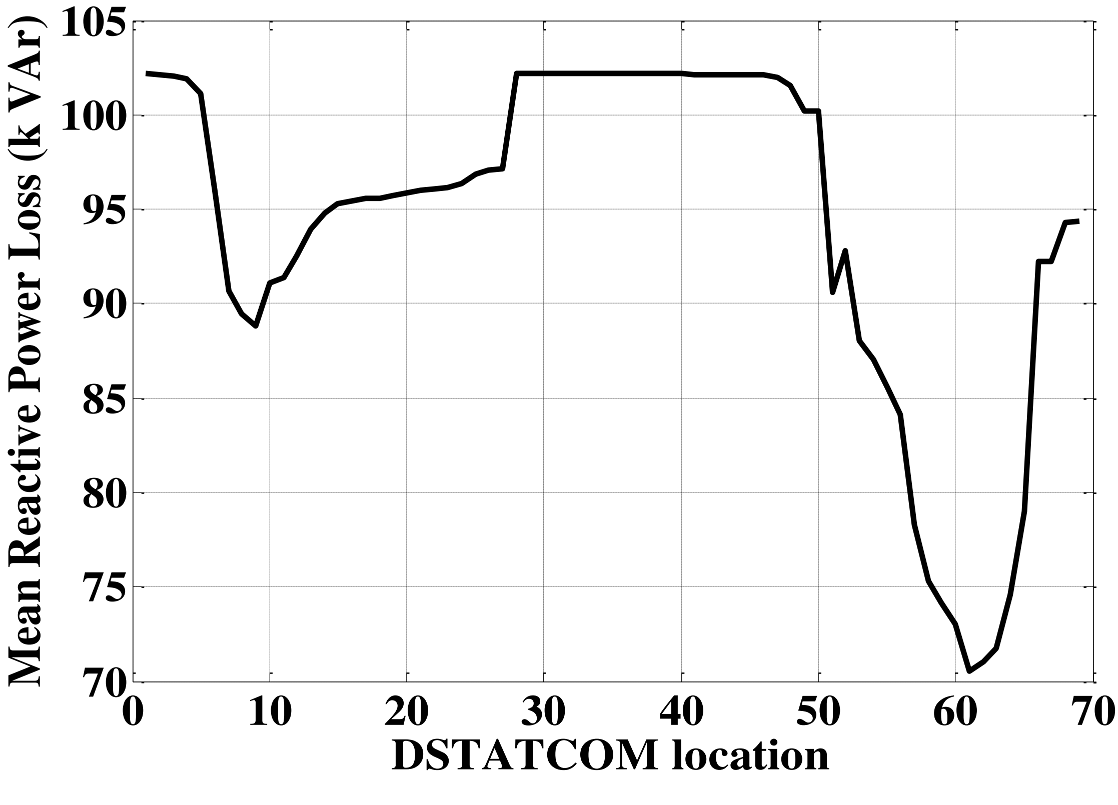

Figure.3.14: Minimum reactive power loss in each node due to DSTATCOM

3.4.2. Results of DSTATCOM allocation using DE

The proposed algorithm is used in the determination of the optimal allocation of single DSTATCOM. The active power loss corresponding to the best solution in each generation of DE with single DSTATCOM allocation is shown in Fig. 3.15. It is observed that the minimum power loss from generation to generation from 1^{st} to 11^{th} generation has been reduced. After the 11^{th} generation minimum power are converged beyond which the minimum power loss remains same. The time to get convergence of an objective function seems very less in DE algorithm. The same can be observed in the rest of the DE based simulation results. Therefore, DEA is very fast and effective evolutionary algorithm to optimize the variable of fitness function. The mean active and reactive power loss of the population in each generation of DE is shown in Fig. 3.16. and Fig. 3.17 respectively. The minimum active and reactive power loss are found to be 152.04 kW and 70.56 kVAr respectively with a 27.49° optimal phase angle injected by DSTATCOM allocation at bus 61. It is attention grabbing that the optimal phase angle obtained by ESM algorithm found to be almost same in Fig. 3.10 compared to the DE based algorithm.

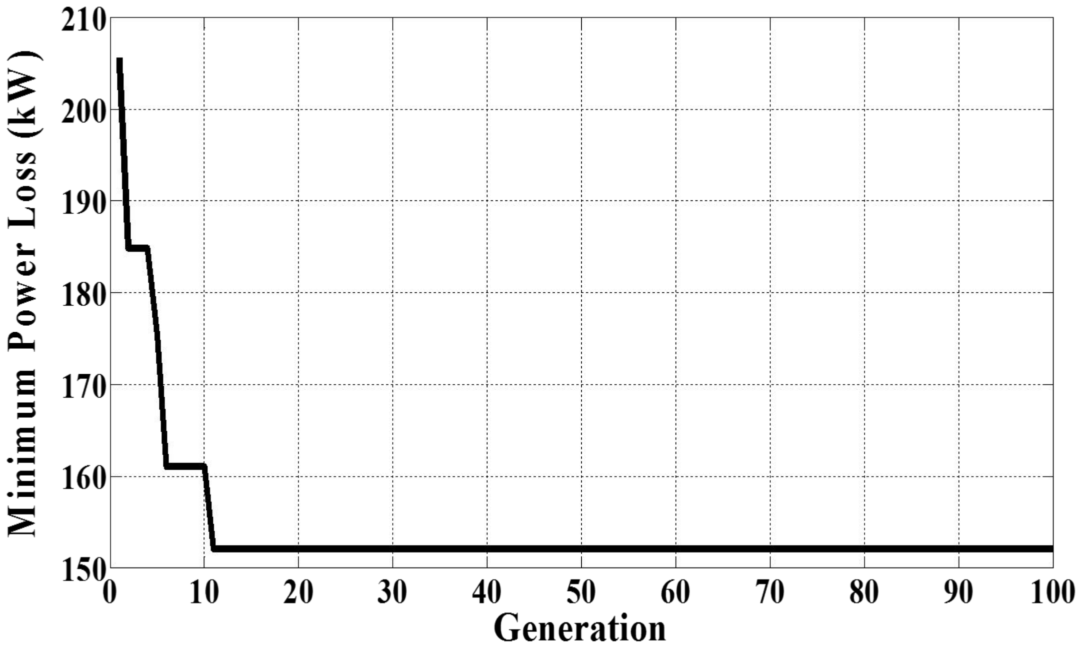

Figure.3.15: Minimum active power loss of each generation with single DSTATCOM allocation

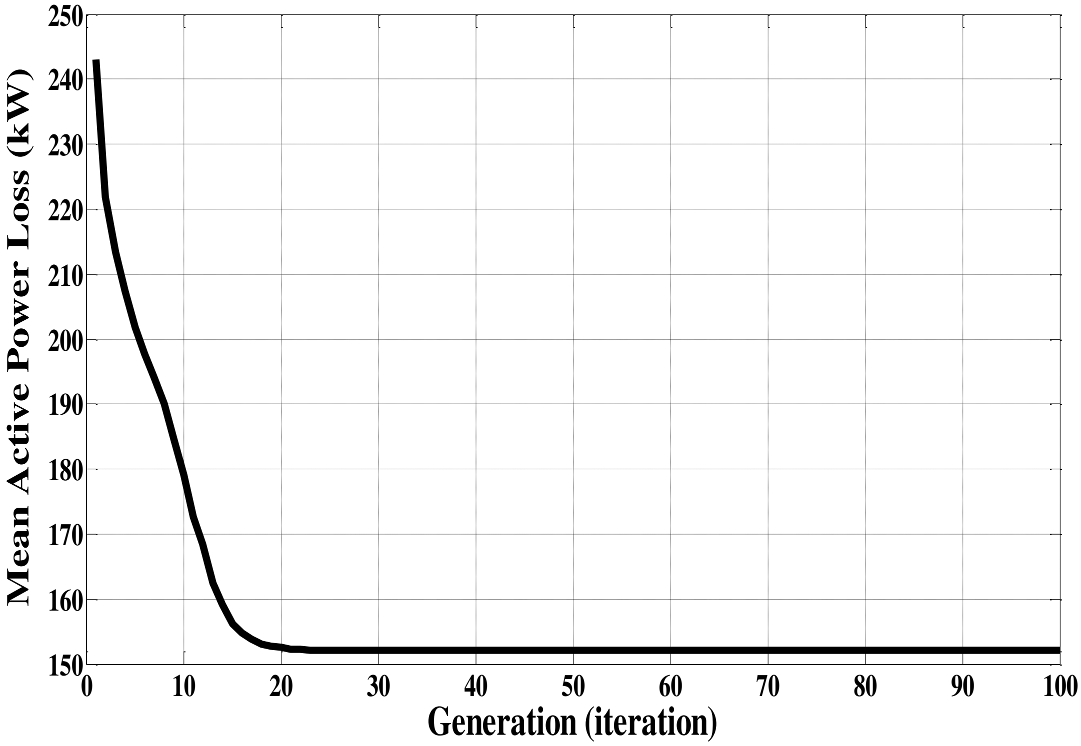

Fig. 3.16: Mean active power loss of each generation with DSTATCOM allocation

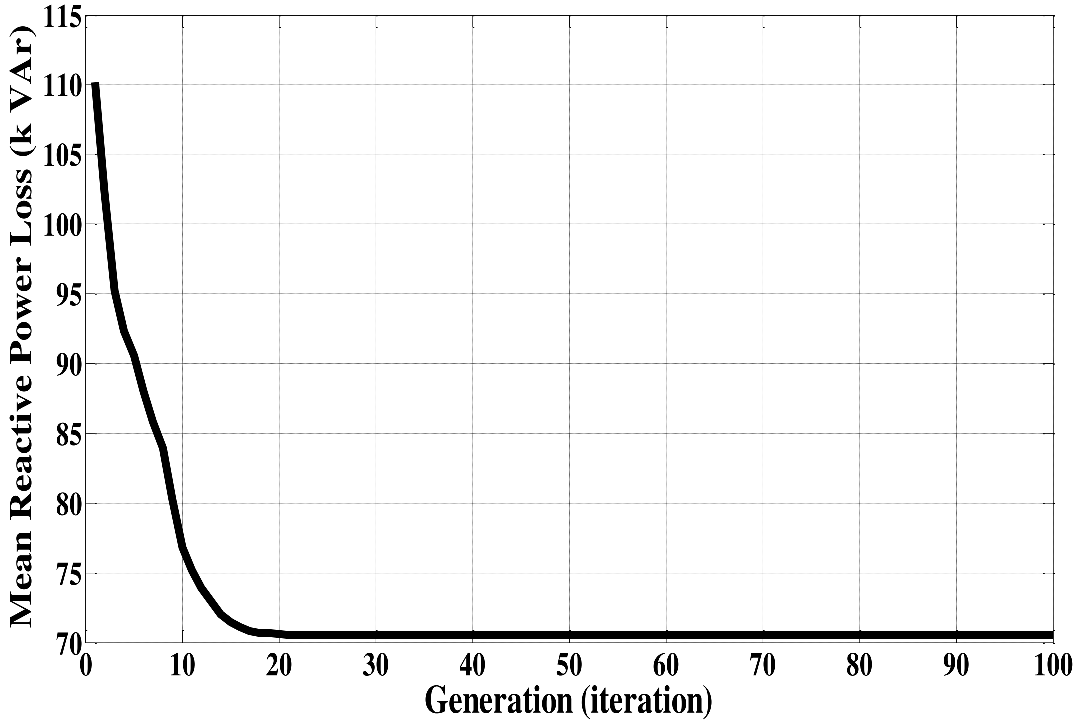

Fig. 3.17: Mean reactive power loss of each generation with DSTATCOM allocation

3.4.3. Comparative results with some of the previous works

The result obtained with the proposed approach using DE is compared with those obtained with the AIS-based approach [88] and PSO-based approach [87] in Table 3.6. It is interesting to see that the optimal location for DSTATCOM allocation is found to be same, i.e., at bus 61 in all the three approaches. However, the rating for DSTATCOM is different. As compared to the AIS-based approach [88], the solution obtained with the proposed approach provides better active power loss with lower rated DSTATCOM. The solution obtained with proposed approach also provides much lower active power loss as compared to the PSO-based approach [87].

The simulation results obtained in this approach proves that the allocation of phase angle model of DSTATCOM compensates the reactive power in RDS to reduce the objective function. The reduction of objective function i.e. the reduction in power loss and improvement in bus voltage profile of RDS reduces the energy loss cost of the RDS and brings economic cost benefit to the distribution companies. The total cost of DSTATCOM installation scheme, reduced energy loss cost, increased profit of various RDS and new objective function, which comprises all these objectives have been investigated and described in the next chapter.

Table 3.6: Comparative results with single DSTATCOM allocation

Operational Aspects	**Without DSTATCOM**	**With DSTATCOM allocation**		
		Proposed approach using DE	**AIS-based approach [88]**	**PSO-based approach [87]**
Location	---	61	61	61
Optimal angle (β'_{n+1}) (Degree)	---	27.49	--	--
Active power Loss (kW)	224.9	152.04	157.5	167.9
MVA rating	---	1.312	1.704	0.901

3.5. Conclusion

In this paper, the proposed DSTATCOM model is incorporated into the Forward/backward sweep load flow algorithm so as to study its impact on the network active and reactive power loss and voltage profile. The 30, 69-bus RDS are used in the case study. The study shows that the network active and reactive power loss can significantly be reduced with a DSTATCOM placement at optimal location with optimal phase angle. Two-optimization approaches ESM and DE have been proposed to determine the optimal location and size for DSTATCOM. The study reveals that significant active and reactive power loss reduction is possible with a DSTATCOM allocation at optimal location with optimal phase angle in a distribution systems. In comparison with some of the previously published works, the allocation of the proposed DSTATCOM model results in comparatively lower active power loss.

Chapter 4

Optimization of Planning Cost of Distribution Systems with the Optimal Placement and Sizing of DSTATCOM Using Differential Evolution Algorithm

4.1. Introduction

This chapter presents an optimization of planning cost of DS with the optimal allocation and sizing of DSTATCOM using DEA. In this appraoch the optimization of planninng cost of DS comprises optimization of energy loss cost (ELC) of DS, and the optimal allocation and sizing of DSTATCOM to maximizing the total net profit (TNP)/cost savings per annum and planning horizon (PH) of DSTATCOM installation scheme. In this approach, the optimal reactive power compensation is the main vital role in solving the objective function. The optimal reactive power compensation with the optimal placement and sizing of DSTATCOM and the improvement in voltage profile of the DN are obtained based on certain objectives such as best reduction in network power loss and the total ELC and the maximization of TNP. A new phase angle modeling on the size of DSTATCOM was incorporated in DN through the forward-backward sweep load flow technique as described in chapter 2 to evaluate the parameters of load flows in DN. Present worth factor (PWF) is instigated to evaluate the TNP of the DSTATCOM installation scheme. The proposed method is validated on the 30-bus, 33-bus, and 69-bus RDS. The simulation results obtained in this approach are compared with the some of the previous investigations and found to better.

4.2. Importance of Planning

In order for the industry to remain profitable, the principal company must obtain the least amount of total cost of ownership. This means selecting system configurations with low cost by also accounting for cost of operation, maintenance & upgrades, and system decommissioning. Planning is necessary to design a system for optimum performance.

While ensuring supply continuity, minimizing power losses, ensuring power quality, and obtaining trouble free operation by selecting appropriate sizing equipment based on surrounding influences. The planning of electric power distribution in buildings and infrastructure facilities is subject to constant transformation. The search for an assignment-compliant, dependable solution should fulfil those usual requirements placed on cost optimization, efficiency, and time needs.

4.3. Planning for Industrial Distribution Systems

Planning begins with assessing the predetermined energy demand for the facility. To understand what the facility would require for energy consumption prior information of other facilities projects with similar equipment and processes is a good starting point. This only provides a starting point, where a better approximation can be determined based on facility machinery and equipment. Data required to be collected for power estimation include:

1. List of connections loads and locations
2. Pattern of loading (process variations)
3. Separating critical load from non-critical loads
4. Loads with high harmonics
5. Inclusion of future growth plans
6. Utility interfacing

A list of load locations and pattern of equipment loading will aid in assessing the load factor, demand factor, and diversity factor. Application of these factors is crucial in accurately estimating power requirements for any facility and designing distribution systems.

Power distribution systems require large amounts of funds for investments in any industry and a sizeable amount for operational costs. Proper planning for designing a distribution system with optimum performance requires several steps from collecting data, selecting proper configurations, and selecting appropriate equipment using planning tools, and software for modeling and documenting important aspects of the distribution system.

4.4. Mathematical problem formulation

4.4.1 Objective function (F)

The proposed method is mainly aimed to obtain the location and the size (kVAr rating) of DSTATCOM in a RDS, in a steady state condition to optimize the objectives such as voltage profile improvement and power loss thereby optimizing total planning cost of RDS to achieve the maximization of total net profit (TNP). Hence, minimization of energy loss cost (ELC) (f_1) and total planning cost of DSTATCOM (f_2) in RDS are considered in objective function (F). Penalty factor is added to the 'F' when the voltage, current and reactive power constraints are violated. The power (energy) loss, and total planning cost of the RDS, are calculated under three load levels (Light, Medium and Peak levels) in the network for a given period 'T' as shown in Table 4.3. Here the load duration curve is estimated by a piecewise function and load level is assumed constant during the period T, divided into discrete intervals as shown in Fig. 4.1 [88] and [99].

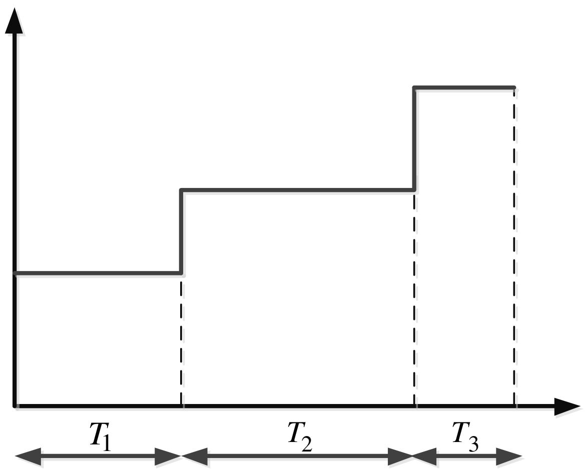

Figure.4.1: Time Duration Curve

The objective function is mathematically expressed is given by Eq. (4.1)

$$F = \min\left((f_1) + (f_2)\right) \tag{4.1}$$

The first part of 'F' is the total energy loss cost (f_1). The primary goal of DISCOs is the loss reduction to maximize the profit. The second part is the total cost of DSTATCOM (f_2) that includes initial capital investment cost, the operating and maintenance (O&M) cost (running costs) of the DSTATCOM placed in RDS. The total planning cost of RDS depends on the amount of power loss reduction, which is absolutely depended on the size of DSTATCOM allocated optimally on the network**.** However, the installation of DSTATCOM increases the planning cost. Therefore, the objective of optimal DSTATCOM placement problem, in this case, is to minimize the total cost for planning the RDS and is defined by the Eq. (4.2). [83], [111]

Objective function= $F = (f_1 + f_2) \times [PF]$ (4.2)

$$f_1 = E^{DSTAT}_{Loss\ Cost} = \sum_{y=1}^{ph} \left[C_e \sum_{k=1}^{nl} P^{DSTAT}_{Loss_k} \times T_k \times PWF \right] \times [PF] \quad (4.3)$$

$$f_2 = DSTAT_{Total\,Cost} \left(f_{21} + f_{22} + f_{23} \right) \times [PF] \quad (4.4)$$

$$f_{21} = \sum_{k=1}^{nl} (k_{ck} \times C_{in} \times Q_k^{DSTAT}) \times PWF \quad (4.5)$$

$$f_{22} = \sum_{y=1}^{ph} \left[\sum_{k=1}^{nl} (k_{ck} \times C_{op} \times Q_k^{DSTAT}) \times PWF \right] \quad (4.6)$$

$$f_{23} = \sum_{y=1}^{ph} \left[\sum_{k=1}^{nl} (k_{ck} \times C_{in} \times Q_k^{DSTAT}) \times C_{ma} \times PWF \right] \quad (4.7)$$

Where '*PF*' is the penalty factor shown in Eq. (4.12), f_{21}, and f_{22} and f_{23} are the total initial capital investment cost and the total operational cost and the total maintenance costs of the DSTATCOM respectively in the whole PH of DSTATCOM installation scheme. The f_{21} is considered per year in three load levels since it is installed only once for the total planning horizon. C_e is the energy cost per kWh; T_k is the duration of time in k^{th} load level; C_{in} is the initial capital investment cost(purchase cost) of DSTATCOM per kVAr; C_{op} is the operational cost of the DSTATCOM per kWh; C_{ma} is the DSTATCOM maintenance cost which in terms of the % of initial cost of DSTATCOM per a year; Q_k^{DSTAT} is the size of the DSTATCOM placed at optimal location during k^{th} load level ; k_{ck} is the proportionality constant of k^{th} load level time duration to the total duration of the time formulated as following Eq. (4.8)

$$k_{ck} = \frac{T_k}{\sum_{k=1}^{nl} T_k} \tag{4.8}$$

4.4.2 Real power loss

The optimal variables, such as optimal location for DSTATCOM and the corresponding size through the optimal angle β'_{n+1} are determined by Eq. (2.11) to get the lowest total power loss and improvement in the voltage profile. The real power loss encountered in Eq.(3.1) is expressed by Eq. (4.9). [97].

$$P_{Loss_k}^{DSTAT} = \sum_{k=1}^{nl} \left[\sum_{j=1}^{n-1} I_b^2(j) \times R_b(j) \right] \tag{4.9}$$

Where $P_{loss_k}^{DSTAT}$ is the active power loss during k^{th} load level after DSTATCOM is installed, *nl* is the number of load levels given in Table 4.3, *k* is the load level, *n* is the total number of buses in the DN, $I_b(j)$ and $R_b(j)$ are the line current and the resistance of j^{th} branch respectively.

4.4.3 Present worth factor (PWF) analysis

To evaluate the economic value of the DSTATCOM installation scheme, it is required to compare the expected revenue and investment costs over the whole *PH* of DSTATCOM installation scheme. In the proposed objective function as given in Eq. (4.3), the *PWF* principle is adopted for cost-benefit analysis of the scheme. The *PWF* offers a net worth of the scheme in today's dollars by discounting each year's cash flow back to the present and then, deducing the initial investment. The mathematical expression of *PWF* is expressed by Eq. (4.10): [112]-[114].

$$PWF = \frac{(1+\gamma)^y \times \gamma}{(1+\gamma)^y - 1} \tag{4.10}$$

Where *y* is the total planning horizon, γ is the discount rate of interest considered as 10% for each annual period. The total cost of energy loss, initial capital investment, operational and maintenance costs of DSTATCOM placed at interest, compounded annually at γ percent for *'y'* years equals to the *PWF*. In another words, the *PWF* is simply the reciprocal of the foregoing compounding factor. It is inescapable that if we provide for a return we must also discount all future costs. It must be noted that the *PWF* does not imply an appraisal of assets in terms of present day reproduction costs. The *PWF* principle can appraise a long-term plan with the following advantages.

- It can compare the costs and benefits in a logical manner by recognizing the time value of money
- It can adjust the discount rate or expected cash flows in order to incorporate any risk into the valuation of a planning

4.4.4 TNP/Savings:

The TNP which is to be maximized is the difference between the expenditure of the energy loss cost of a DN without DSTATCOM and the total expenditure of the energy loss cost of a DN with the scheme of DSTATCOM. It is given by the Eq. (4.11). [88]

$$TNP = \sum_{y=1}^{ph} \left[C_e \sum_{k=1}^{nl} P_{Loss_k}^{w/o\,DSTAT} \times T_k \times \frac{1}{(1+\gamma)^y} \right] - F \tag{4.11}$$

TNP, in fact, yields an economic savings or benefit in the DN with DSTATCOM for the total PH of DSTATCOM installation scheme, [99] and [102]. Therefore, the purchasing cost of power from substation according to the customer's demand can be reduced.

4.5 Constraints

The proposed Eq. (4.3) is bounded by various active constraints to meet the limitations on DSTATCOM operation and electrical requirements for the DS. Penalty factor is considered when the objective functions f_1 and f_2 are converged as a single objective function and the operating variables such as bus voltages, line currents and the capacity of the DSTATCOM violates the desired safe limits. The soft constraints princple is used in this appraoch to to introduce penalty factor. The minimum and maximum voltages are considered as 0.9 *p.u.* and 1.1 *p.u.* respectively[88] as shown in Table 4.1. If the voltage at bus *i* cross these limits the penalty factor is considered in objective function Eq. (4.3). Maximum limit of the current in the network is taken as 1.2 times the base current of the branch *j*. The line will be melted if the maximum limit of the current exceeds. The maximum capacity of is considered as 10000 kVAr beyond which the penalty factor is considered. The constraints are taken in steady state. The penalty factor used in proposed objective function is given by Eq. (4.12).

$$PF = Penalty\ Factor = \prod_{k=1}^{nl} \left| \left(\prod_{j=1}^{n-1} I_b^{over}(j) \times \prod_{j=1}^{n} V_n^{over} \right) \right| \tag{4.12}$$

Where $$I_b^{over}(j) = \begin{cases} 1; & if\ I_b(j) \le I_b^{Max}(j) \\ \exp\left(\lambda \left| 1 - \frac{I_b(j)}{I_b^{Max}(j)} \right| \right); & if\ I_b(j) \ge I_b^{Max}(j) \end{cases} \tag{4.13}$$

$$V_n^{over} = \begin{cases} 1; & if\ V_n^{Min} \le V_n \le V_n^{Max} \\ \exp\left(\mu \left| 1 - V_n \right| \right); & Orelse \end{cases} \tag{4.14}$$

Penalty factor is used to minimize the deviation of node voltage and line current. '$I_b^{over}(j)$' is the factor of over current flowing through the branches (lines) and 'V_n^{over}' is the over voltage factor. λ and μ are small positive constants. If branch currents '$I_b(j)$' are less than '$I_b^{max}(j)$', then '$I_b^{over}(j)$' will be equal to one. Similarly, 'V_n^{over}' will be equal to unity when bus voltages are within the desired limits. In all other conditions, '$I_b^{over}(j)$' or 'V_n^{over}' shall attain a value (greater than unity) that acts as a penalty factor in objective function Eq. (4.3).

The penalty factor method is an effective constraint handling technique, and it can guide infeasible solutions to move to feasible solutions [115] i.e. it convert a constraint optimization problem into a non-constrained optimization problem when it was added for violation of constraints. In this paper, we adopt a common penalty function method [88] and [116] to handle constrained optimization problems as shown in Eqs (4.12)-(4.14). The

λ and μ in Eqs (4.13) and (4.14) are the small positive constant, and represents the tolerated violation, which imposes penalty on unfeasible solutions. These both constants are set to 0.1 to punish constraint violations [88]. If the penalty value is very high, the feasible region will be approached mostly at random and the feasible global optimum will be hard to get. On the other hand, if the penalty is too low, the probability of not reaching the feasible region will be high. Therefore, the penalty factors must be carefully tuned, as they are problem-dependent. The penalty factor used in proposed approach is taken from IA approach [88] since the effectiveness and performance of proposed approach is compared mainly with IA approach [88].

Table 4.1**:** Constraints considered in proposed approach

S.No	**Name of the constraint**	**Range**	**Min limit**	**Max limit**
1	Voltage	$V_k^{min} \le V_k \le V_k^{\max}$	0.9 p.u.	1.1 p.u.
2	Current	$I_k \le I_k^{\max}$	--	1.2 times base I_j p.u.
3	Reactive power	$Q_{k+1_{\min}}^{DSTAT} \le Q_{k+1} \le Q_{k+1_{max}}^{DSTAT}$	--	10000kVAr

Table 4.2: Parameters of DEA

NP	**D**	**F**	**CR**	**Generations**
50	2	1	0.8	100

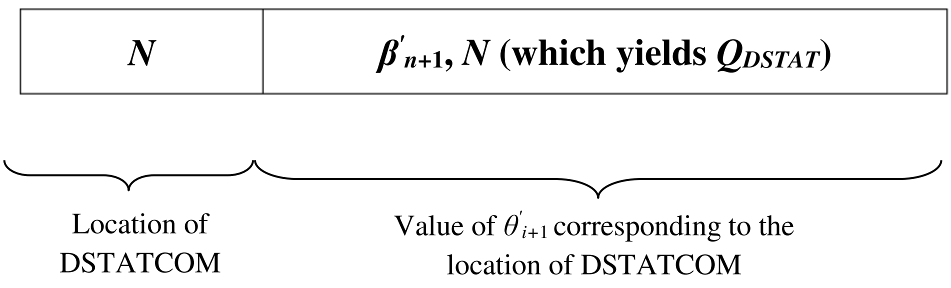

Figure.4.2: A typical string for DEA

The final aim is to minimize the proposed objective function so that all boundary conditions be satisfied. If the solution violates the proposed constraints for the particular candidate locations to obtain the best solution, then it will cause the drastic increase in the value of objective function, which lead to an inappropriate solution [88]. The minimization of objective function enhances the bus voltage profile. However, it should not be enhanced beyond the magnitude of 1p.u. because the power loss in distribution systems are more than transmission systems, which cause the huge drop in the magnitude of the bus voltage as mentioned in section I. Thus, the compensation of reactive power in distribution systems can never enhances the magnitude of the voltage to the value beyond the magnitude of source voltage of the distribution system. However, it may happen when the concept of constraints optimization is not considered in the optimization algorithm, which results the requirement of higher amount of reactive power compensation. Hence, the magnitude of bus voltages obtained in the proposed approach are found to be appropriate since the constraints are imposed. For example, the magnitude of bus voltages as shown in Figs. (4.12), (4.13), (4.16), (4.17), (4.20), and (4.21) have not crossed the voltage magnitude of 1p.u.

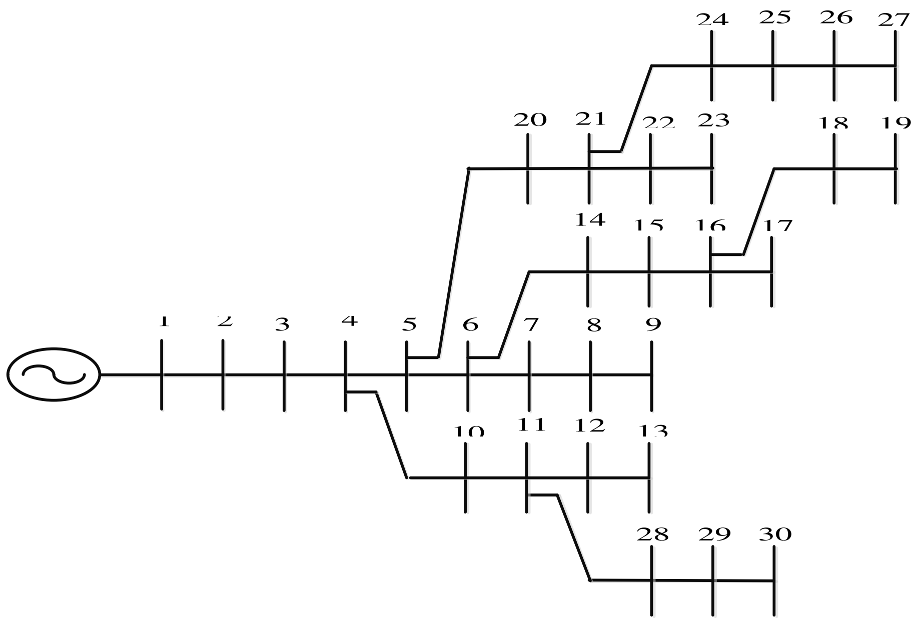

Figure.4.3: Typical IEEE 30-bus DN

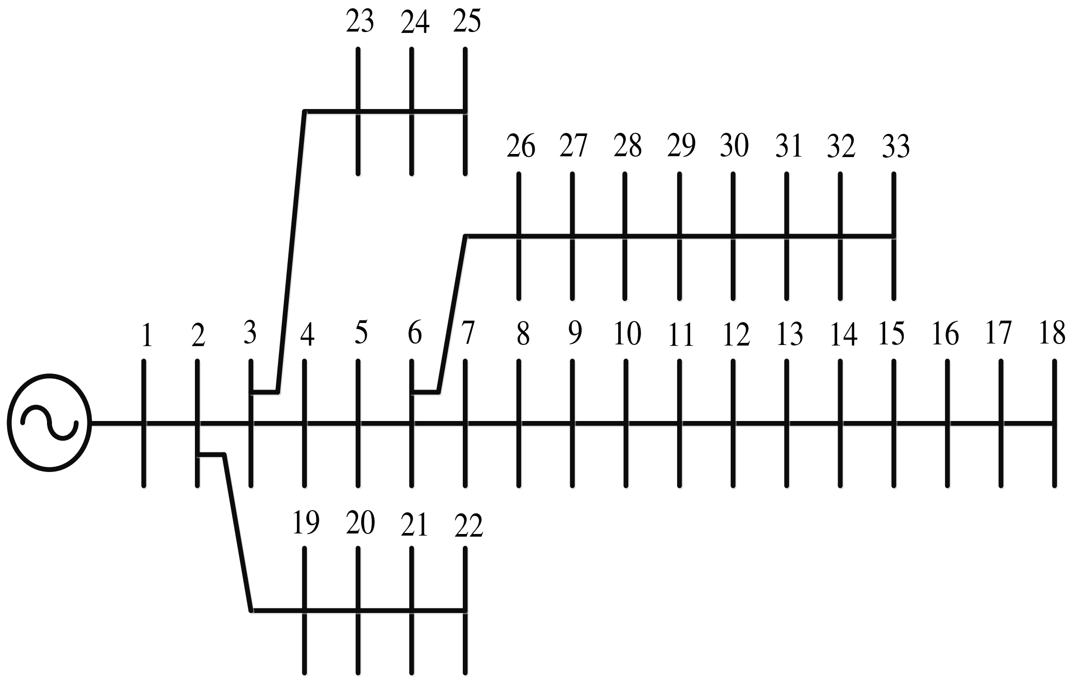

Figure.4.4: Typical IEEE 33-bus DN

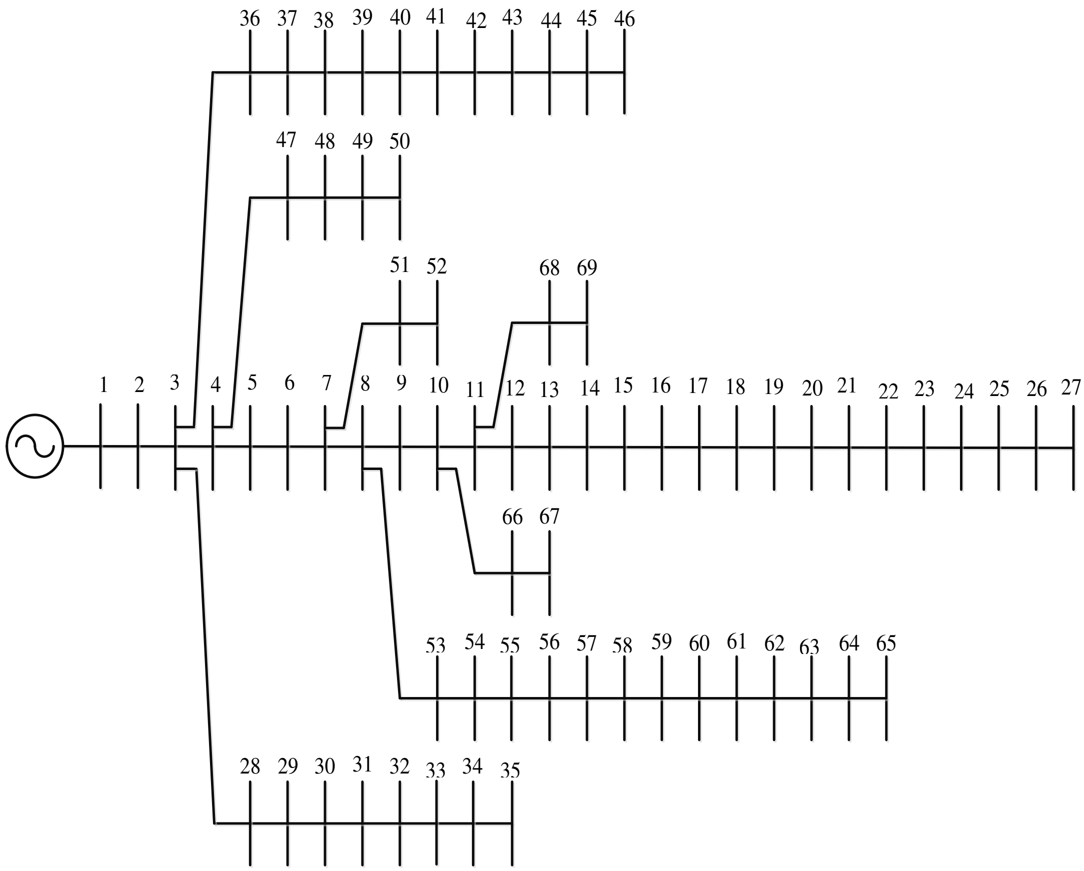

Figure.4.5: Typical IEEE 69-bus DN

4.6 Solution Strategy Using DEA

The main purpose of the DEA in this approach is the minimization of an objective function given in Eq. (4.2) by determining the capacity of the DSTATCOM at the candidate locations. A typical string structure is shown in Fig. 4.2. The candidate locations for DSTATCOM are considered to be all the busses for each load level except the substation bus and the range for the angle β'_{n+1} should lie in between 0 to 90 degrees. The optimal value of β'_{n+1} decides the optimal size of DSTATCOM with the help of Eqs. (2.11) and (2.12) in chapter 2.

Table 4.3: Load duration time and load level

Load level		**Light load**	**Medium load**	**Peak load**
Time duration (hour/year)		2000	5260	1500
Total Load (kVA)	**30-Bus**	1603.2+j1196.4	2084.1+j1196.4	2306.7+j1196.4
	33-bus	3715+j2300	4829.5+j2300	5944+j2300
	69-bus	3802+j2694.6	4942.8+j2694.6	6083.5+j2694.6
Total power loss (kW)	**30-bus**	146.07	220.32	320.02
	33-bus	202.66	305.81	442.39
	69-bus	224.97	342.96	502.47

To study the validity of the proposed approach, three standard sample RDS such as 30, 33 and 69 bus networks are taken [117], [88] and their typical single line diagrams are shown in Figs. 4.3, 4.4 and 4.5 respectively. To assess the virtue of DEA it has been compared with an approach based on IA [88] in view of performance and run on the same parametrical basis. The DEA parameters initial population size (N_P), dimension of each population *(D),* weighting factor *(F),* crossover rate*(CR*), and maximum generations, are taken as mentioned in Table 4.2. Initial strings that are produced randomly, contains bus location for compensation as well as optimal variable angle β'_{n+1} of DSTATCOM for the respective location at all(three) load levels. The objective function is calculated for each string by running Load flow algorithm at all load levels. The fitness (objective) function parameters used in this work are shown in Table 4.4 [88], [118]. The mutation can not guarantee the solutions with the specified range of two different string variables since there is a strong mutual dependence of two variables while encoding the problem. Moreover, the proposed algorithm is a probabilistic algorithm. Hence, to evaluate the performance of proposed algorithm, 50 runs are performed and corresponding suboptimal solutions are obtained. Thus, after the statistical computations the mean value and standard deviation of the total energy loss cost with DSATCOM (f_1) and the total planning cost (F) for the optimal solution obtained with 50 runs are obtained and are given in Table 4.9. The best values of the active power loss, the total energy loss cost with DSATCOM (f_1), and the total planning cost (F) among these 50 runs have been considered respectively as the best solution as shown in Figs. (4.8), (4.9), (4.10), and Tables 4.5, 4.6, and 4.7. In IA algorithm [88], the number of populations, generations and runs are taken as 50, 100, and 50 respectively. The same parameters have been considered in this approach as given in Table 4.2 to show the performance of proposed approach. The computing time of these two algorithms are compared in Table 4.10. It should be noted that the constraint of injected reactive power by DSTATCOM, voltage at each bus and current in each line are considered as steady state as mentioned in subsection 4.4.1 of section 4.4.

4.7 Simulation results

In this section, the impact of DSTATCOM on total ELC of the DN per annum and PH of DSTATCOM installation scheme, under three load levels are analyzed. The usefulness of proposed approach is demonstrated on three RDS as mentioned in section 4.6. Three load levels are selected as referred in subsection 4.4.1 of section 4.4 to model the annual load profile. The time duration, total load for each load level, and base power loss in three load levels are shown in Table 4.3.

Table 4.4: Parameters of objective function

Objective function parameter	**Value**
Number of load levels	3
Cost of energy loss(ke) US($/kWh)	0.06
Cost of DSTATCOM(kin) US($/kVAr)	50
Operational cost of DSTACOM(kop) US($/kWh)	0.02
Maintenance cost of DSTACOM(kma) US($/kWh)	0.05
Discount rate of interest (γ)	0.1
PH (years)	30

Table 4.5: Comparative results of reactive power compensation with DSTATCOM for three load levels

Test network	Approach	Light load level				Medium load level				Peak load level			
		Optimal location	Optimal size (kVAr)	Power Loss (kW)	Min voltage (p.u.)	Optimal location	Optimal size (kVAr)	Power Loss (kW)	Min voltage (p.u.)	Optimal location	Optimal size (kVAr)	Power Loss (kW)	Min voltage (p.u.)
30-bus	**Proposed**	5	1159.6	100.8	0.9358	5	1204.9	166.7	0.9189	5	1271.3	261.2	0.8888
33-bus	**Proposed**	30	1252.7	143.5	0.9256	30	1278.4	241.2	0.9058	30	1314.0	370.4	0.8832
	IA [88]	12	962.4	171.8	--	12	1008.1	272.0	--	12	1222.6	407.7	--
	GA [88]	12	1114.2	173.9	0.9272	12	1376.9	281.4	0.9120	12	1845.4	440.5	0.8977
69-bus	**Proposed**	61	1312.1	152.0	0.9338	61	1360.8	261.9	0.9124	61	1404.0	410.5	0.8899
	IA [88]	61	1704.4	157.5	--	61	1911.2	274.4	--	61	2606.8	472	--
	DE [57]	61	924.0	158.6	0.9246	--	--	--	--	--	--	--	--
	GA [88]	61	1918.3	165.4	0.9392	61	2223.2	292.1	0.9209	61	2883.0	502.6	0.9061
	PSO [87]	61	1901.0	167.9	0.9389	--	--	--	--	--	--	--	--

4.7.1 *Impact of DSTATCOM allocation*

When DSTSTCOM is allocated one at a time at each bus except substation bus, there is a significant reduction in power loss and an improvement in minimum bus voltage of the DS at some certain buses. Figs. 4.11 and 4.12 show the impact of DSTATCOM on power loss and minimum bus voltage of IEEE 30-bus DN respectively, and It is observed that these parameters have been affected much when DSTATCOM is placed at buses 3-7, 10, 14, 20 and 21. The DSTATCOM location corresponding to the minimum power loss is found to be bus 5. Thus, the voltage profile of the network with and without DSTATCOM allocation at bus 5 is shown in Fig. 4.13. Similarly, Figs. 4.15 and 4.16 demonstrate the impact of DSTATCOM on power loss in IEEE 33-bus DN respectively.

Table 4.6: Comparative results of annual cost of RDS with DSTATCOM installation without considering operational and maintenance cost of DSTATCOM

Test network	**Total energy loss cost without DSTATCOM($)**	**Approach**	***F ($)***		***TNP ($)***
			f_1 ($)	f_{21} ($)	
30-bus	1,16,374	**Proposed**	89,127	6,399	20,848
33-bus	1,60,670	**Proposed**	1,26,679	6,780	27,211
		IA [88]	1,43,160	5,989	11,521
		GSA [119]	--	--	12389
69-bus	1,80,470	**Proposed**	1,37,841	7,198	35,431
		IA [88]	1,47,980	10,518	21,972
		GSA [119]	--	--	12837

Table 4.7: Results of total costs considering PWF for PH of DSTATCOM installation scheme, including operational and maintenance cost of DSTATCOM

Test network	**Total energy loss cost without DSTATCOM($)**	***F($)***		***TNP ($)***	***TNP (%)***
		f_1($)	f_2($)		
30-bus	6,99,570	5,32,630	6,861	1,60,078	22.88%
33-bus	9,69,976	7,64,873	7,275	1,97,827	20.39%
69-bus	10,89,530	8,32,268	7,722	2,49,540	22.90%

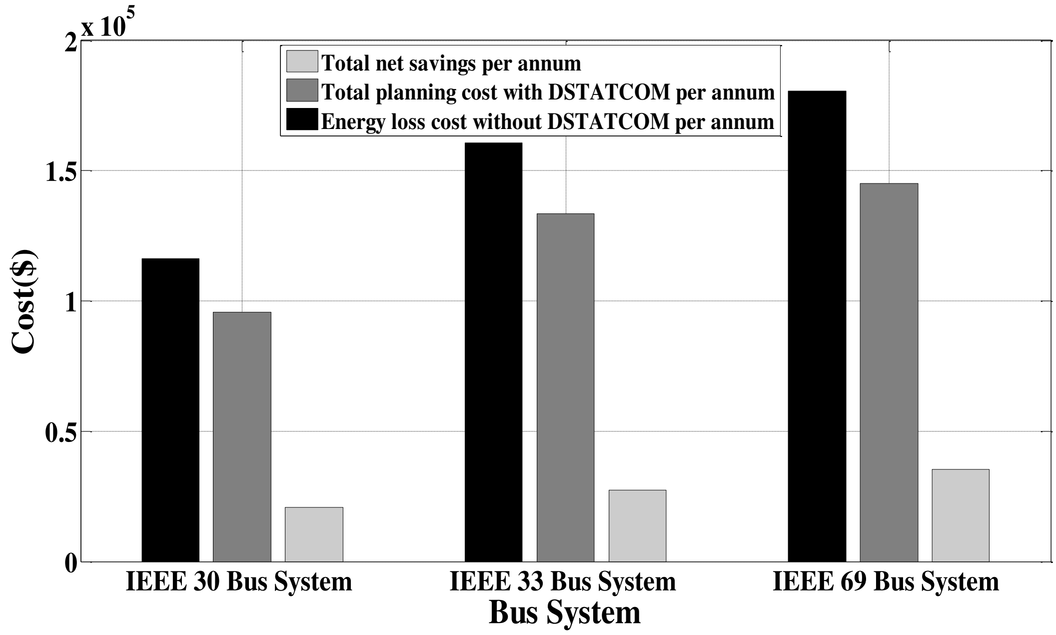

Figure.4.6: Cost analysis per annum

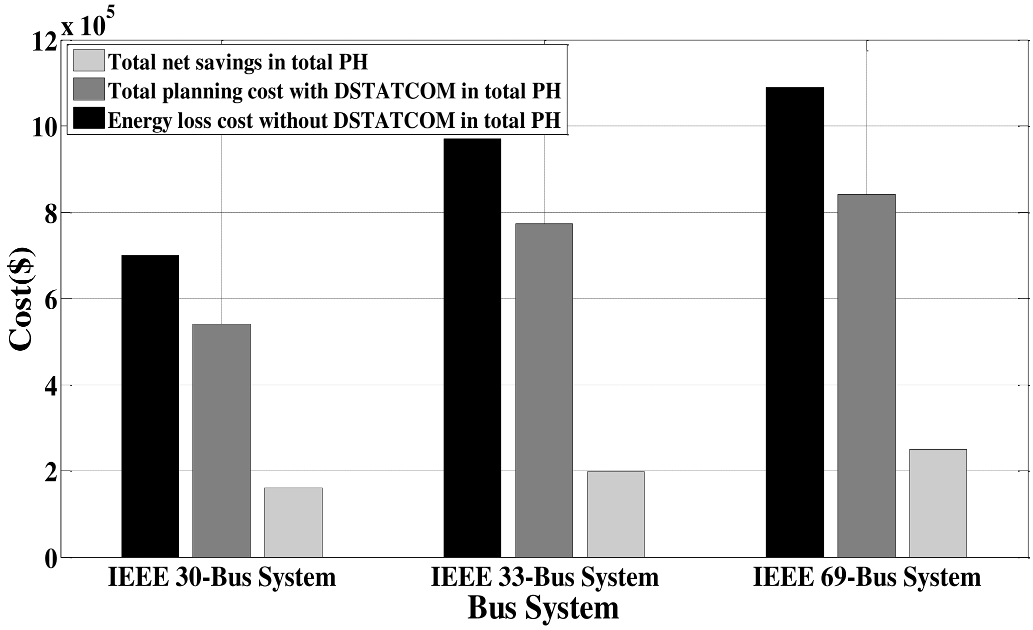

Figure.4.7: Cost analysis of total PH of DSTATCOM installation scheme

It is observed that the buses 3-18, 23 and 26-33 have been affected much in view of power loss and minimum bus voltage and the DSTATCOM location corresponding to the minimum power loss is found to be bus 30 and there is a significant improvement in voltage profile as shown in Fig. 4.17. The plots that are shown in Figs. 4.19 and 4.20 speak of the impact of DSTATCOM on power loss and minimum bus voltage in IEEE 69-bus DN respectively, and it is observed that these parameters are affected much when

DSTATCOM is placed at the buses 6-27 and 51-69. The DSTATCOM location corresponding to the minimum power loss is found to be bus 61 and accordingly the voltage profile of the network with and without DSTATCOM is shown in Fig. 4.21.

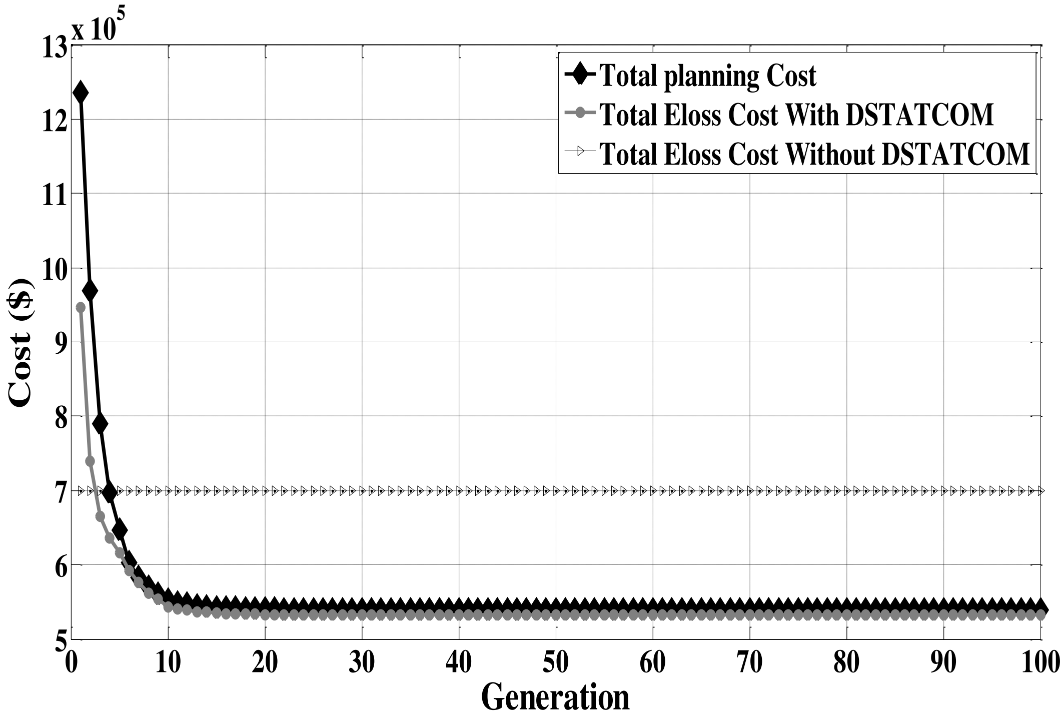

Figure.4.8: Total scheme mean cost of IEEE 30-bus distribution network

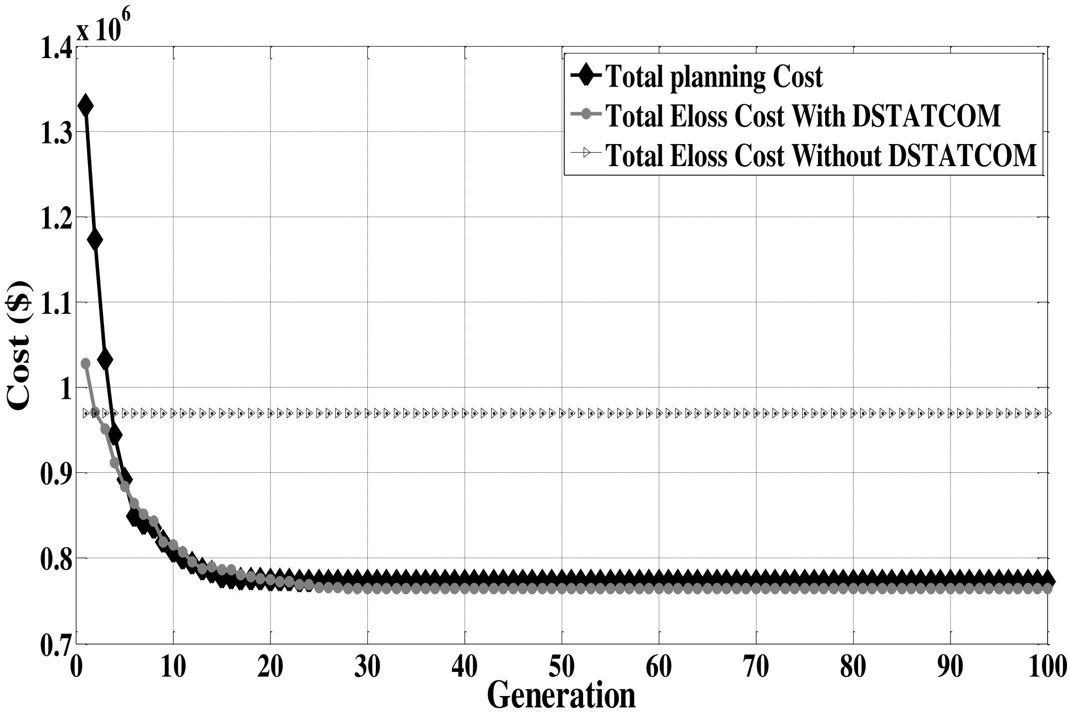

Figure.4.9: Total scheme mean cost of IEEE 33-bus network

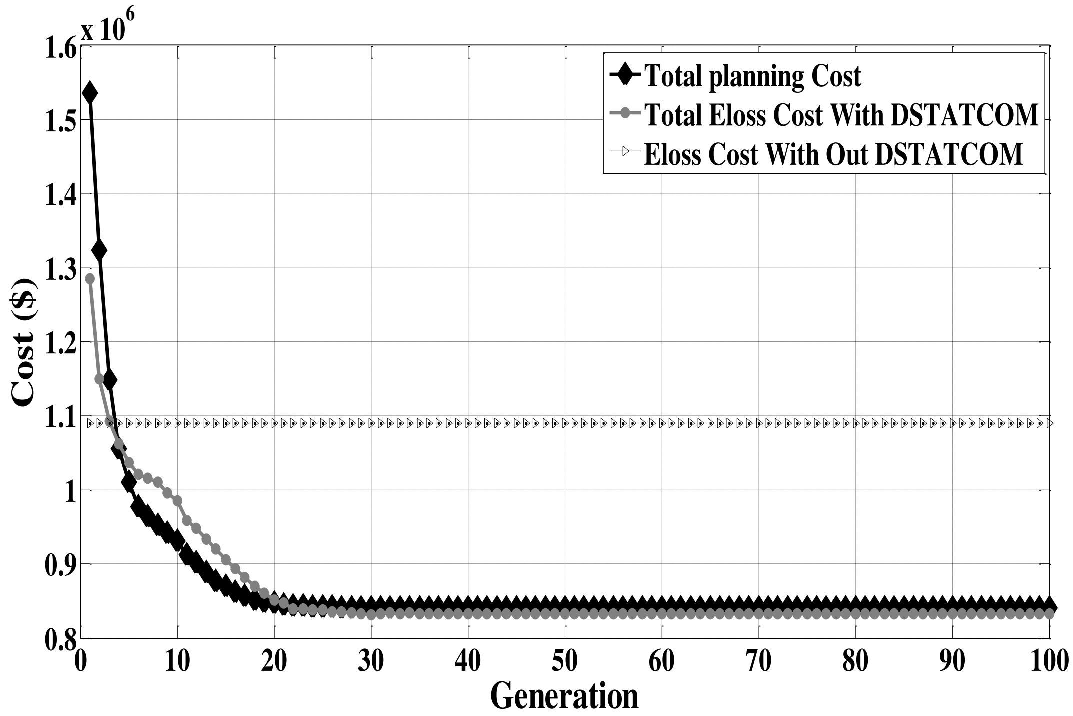

Figure.4.10: Total scheme mean cost of IEEE 69-bus distribution network

4.7.2 Analysis of power loss reduction

Power loss depends on branch current (I_b) and resistance (R_b) since $P_{loss}=I_b^2R_b$ according to the Eq. (4.9). If 'I_b' increases P_{loss} will also increase. Basically, 'I_b' depends on two currents. One is the load current at the sending end bus according to the Eq. (2.28) and the other is the lateral branch currents connected to that bus according to the Eq. (2.29) of chapter 2. If the demand of the load at the bus is high, then the current drawn by the load is high. This results in an increase in 'I_b', which in turn causes the increase in P_{loss}. Also, the bus voltage will fall due to the increase in voltage drop in the branch. To minimize the power loss, should either active power be injected or reactive power be compensated, which in turn causes the decrease in 'I_b'. When 'I_b' is decreased the voltage drop in the branch will be decreased, and thus there is an improvement in the bus voltage profile. The proposed approach aims mainly to compensate the reactive power in RDS to minimize the power loss, ELC, and to improve the TNP and voltage profile using DSTATCOM. If DSTATCOM voltage is greater than the bus voltage while it is being located in the bus, then DSTATCOM injects current into the bus with a phase angle of 90 degrees as shown in Eq. (2.8) and Fig.2.8 in chapter 2.

Thus, the reactive power demand shall be compensated which minimizes the power loss and improves the bus voltage eventually. In the case of the 33-bus DN the complex load power demand ($P+jQ$) at “bus 30” is higher than the load demand in remaining buses as shown in the network data given in “Table A” in “Appendix.”

Mainly, the reactive power demand in “bus 30” is higher than all loads connected in remaining buses. Hence, it is quite natural that the compensation of reactive power highly occurs at “bus 30”. Thus, in proposed approach, the best location for DSTATCOM allocation is found to be “bus 30” with the size of 1252.7 kVAr as shown in “Table 4.5.” Hence, there is certain impact on network power loss when DSTATCOM is located at buses 3-18, 23 and 26-33. In case of the 69-bus DN, the load power demand at “Bus 61” is higher than those of the remaining buses as shown in the network data in “Table B” in “Appendix.” Hence, the best location for DSTATCOM allocation is found to be at “bus 61” with the size of 1312.1 kVAr as shown in “Table 4.5.” There is the certain impact on network power loss when DSTATCOM is located at buses 6-27 and 51-69 as mentioned in section 6.1.

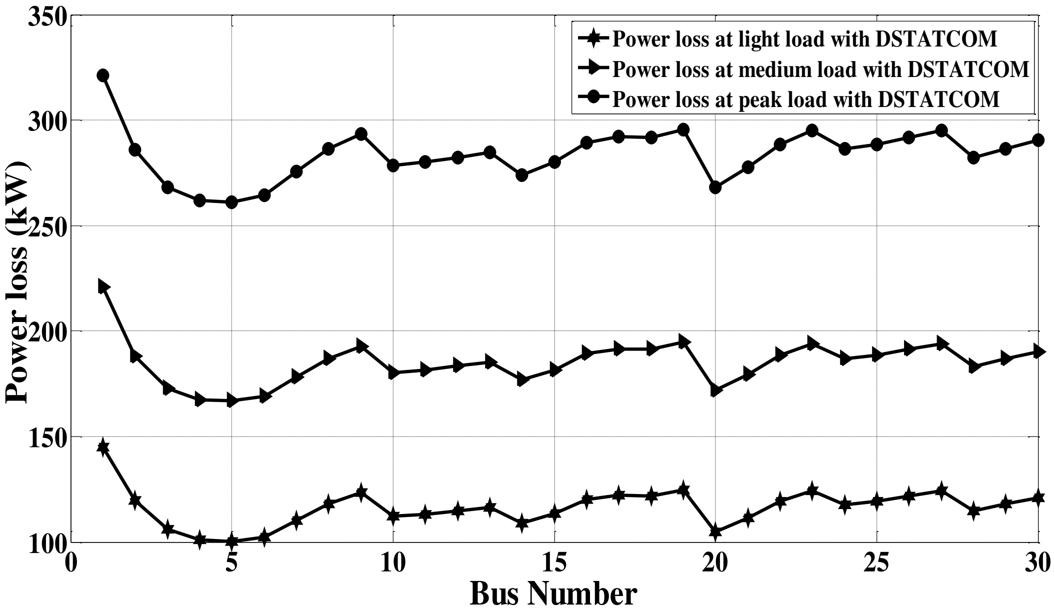

Figure.4.11: Power loss at different loads with DSTATCOM at each bus of IEEE 30-bus distribution network

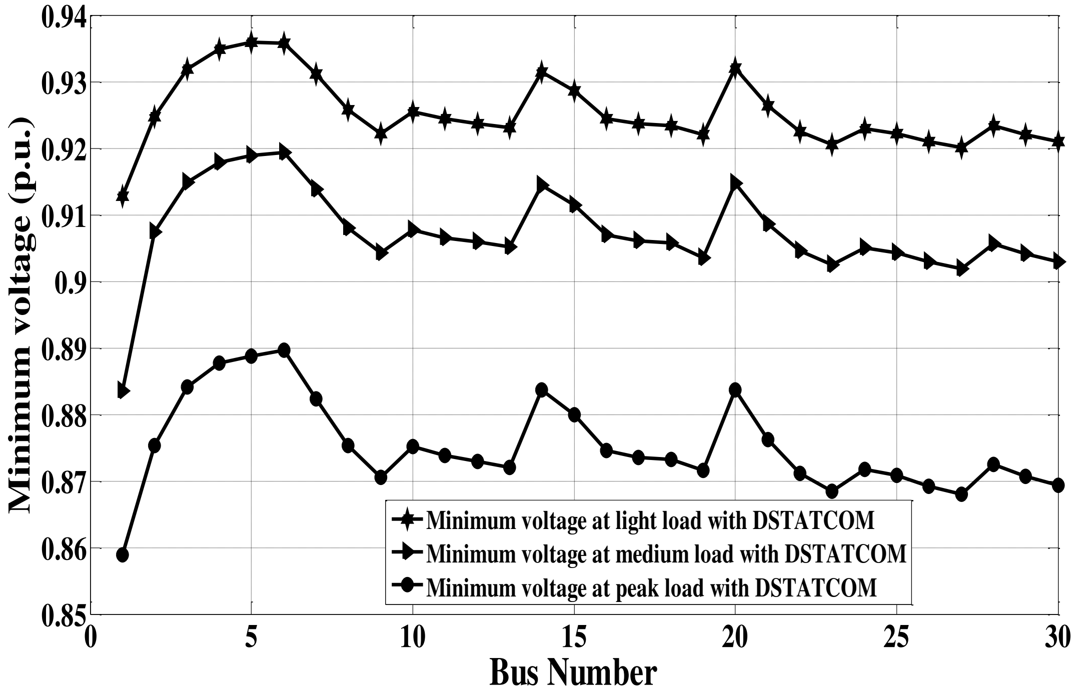

Figure.4.12: Minimum bus voltage at different loads with DSTATCOM at each bus of IEEE 30-bus distribution network

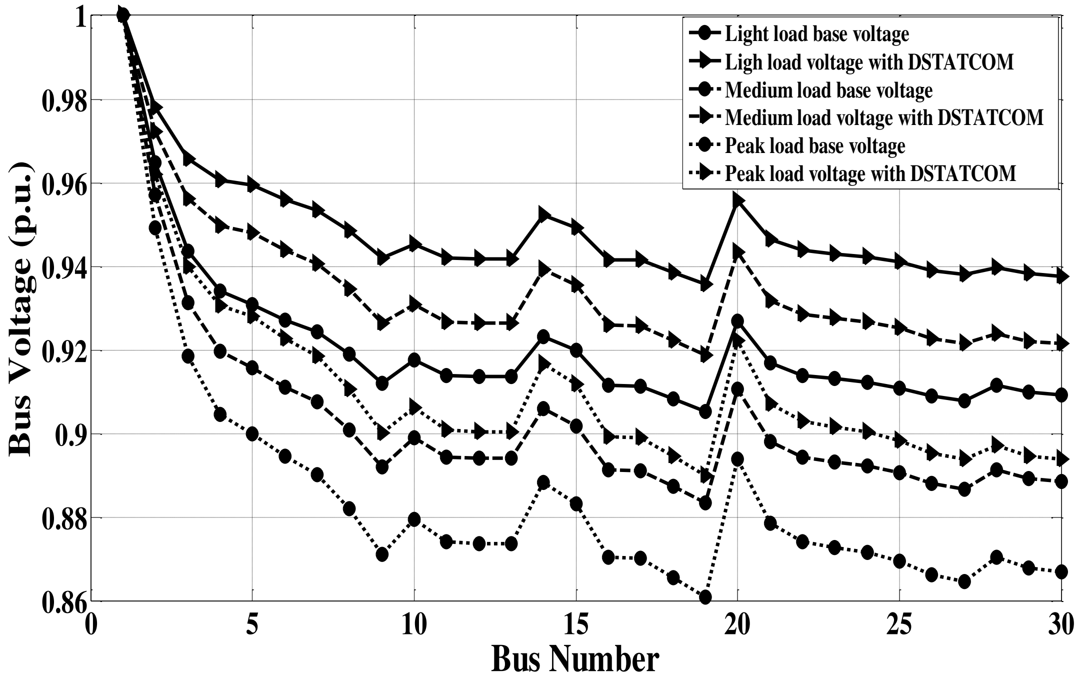

Figure.4.13: Voltage magnitude at various loads with DSTATCOM at bus 5 of

IEEE 30-bus distribution network

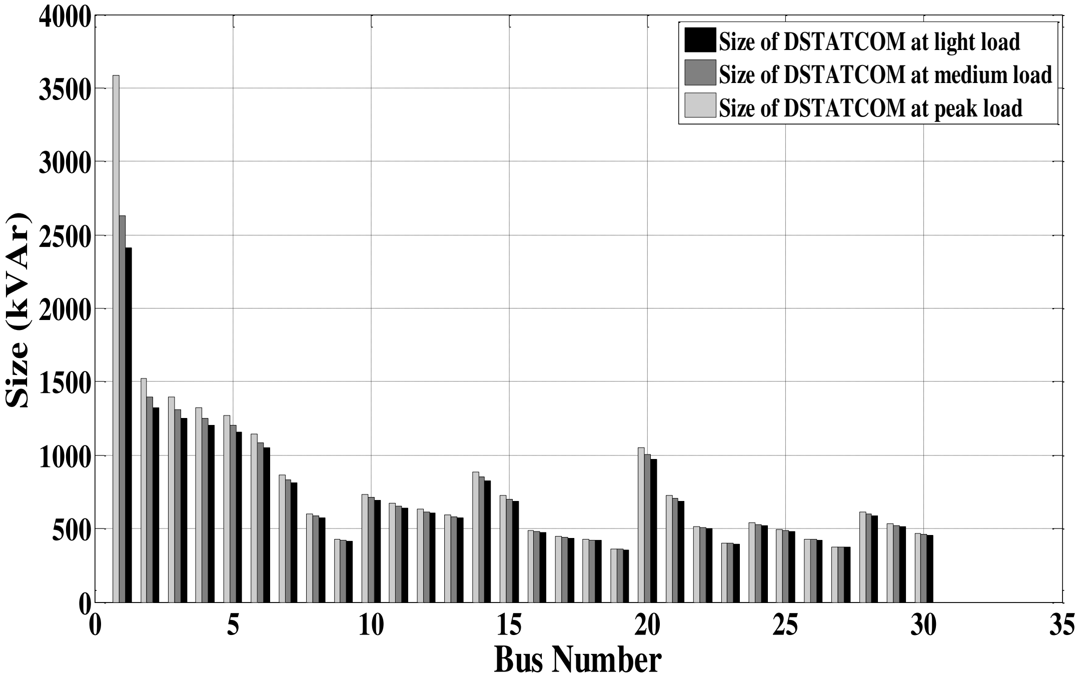

Figure.4.14: Size of DSTATCOM at each bus of IEEE 30-busdistribution network at various loads

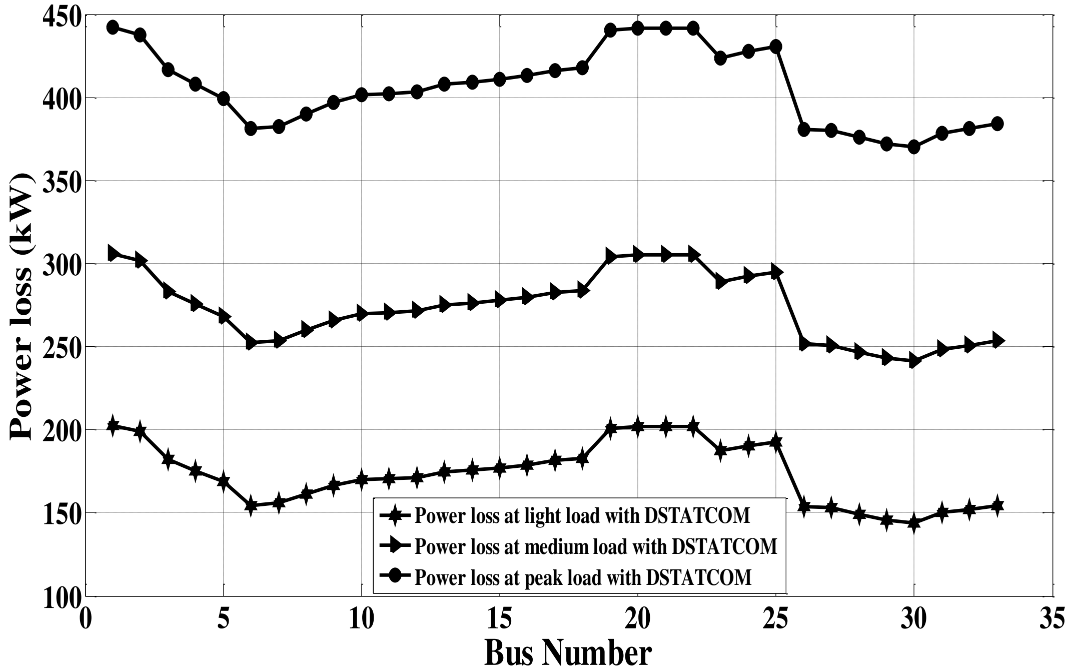

Figure.4.15: Power loss at different loads with DSTATCOM at each bus of IEEE 33-bus distribution network

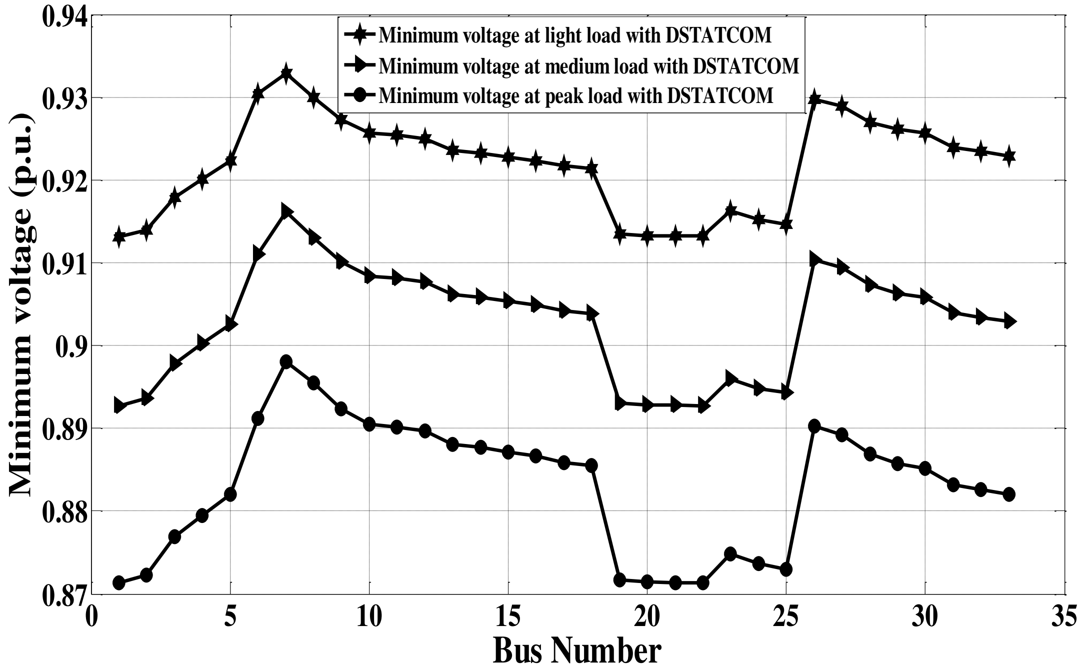

Figure.4.16: Minimum bus voltage at various loads with DSTATCOM at each bus of IEEE 33-bus distribution network

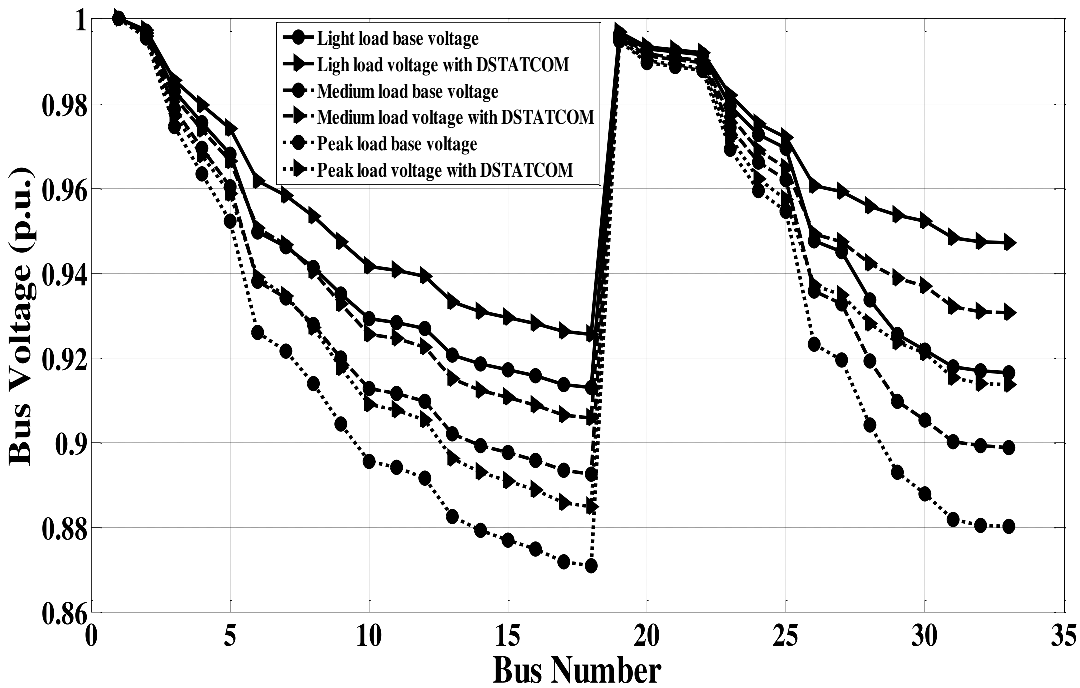

Figure.4.17: Voltage magnitude at various loads with DSTATCOM at bus 30 of IEEE 33-bus distribution network

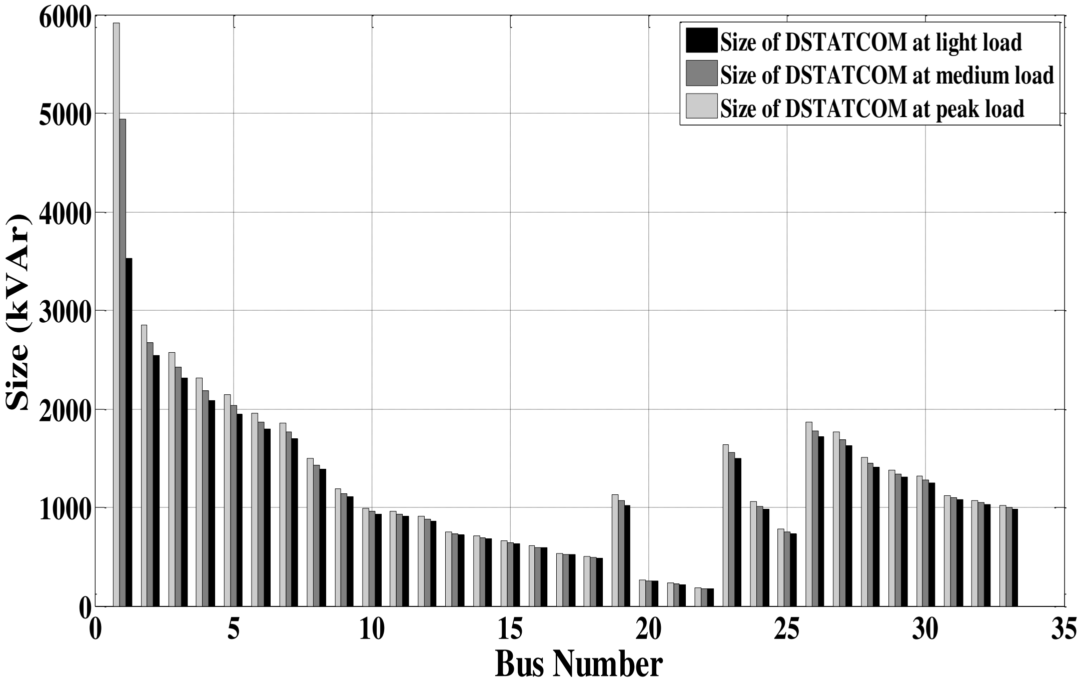

Figure.4.18: The size of DSTATCOM at each bus of IEEE 33-bus distribution network at different loads

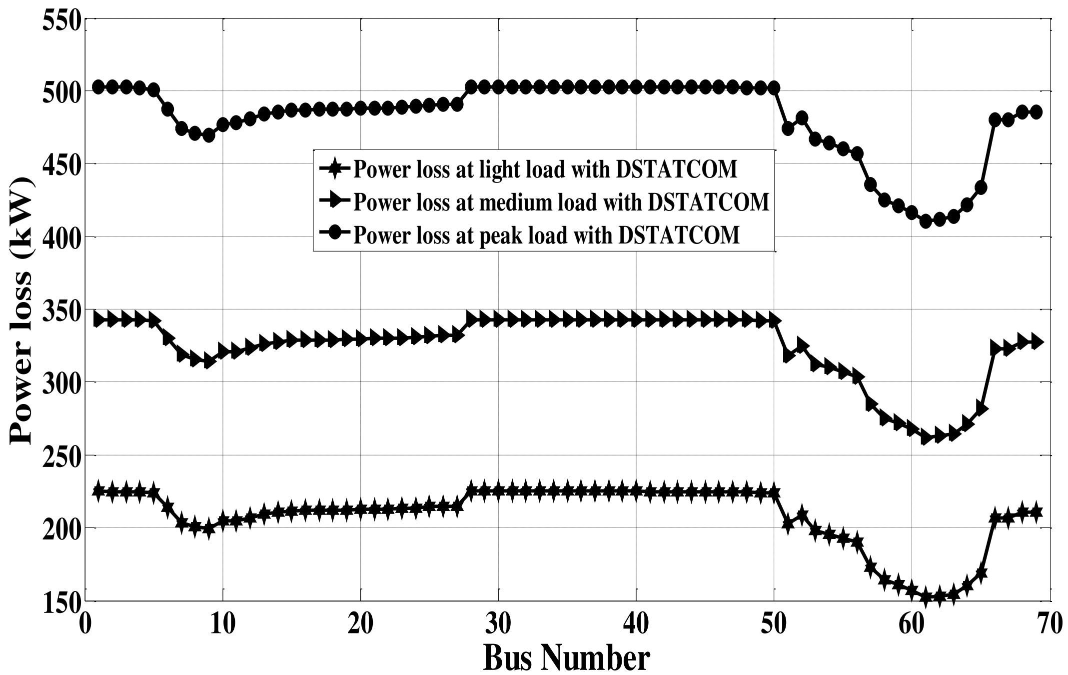

Figure.4.19: Power loss at different loads with DSTATCOM at each bus of IEEE 69-bus distribution network

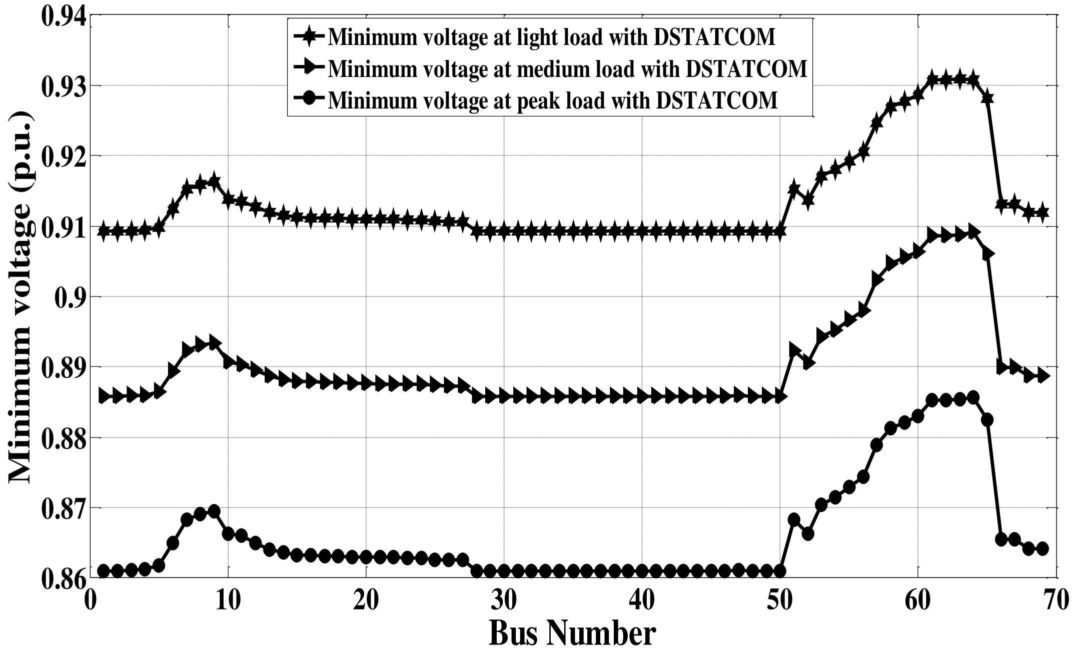

Figure.4.20: Minimum bus voltage at various loads with DSTATCOM at each bus of IEEE 69-bus distribution network

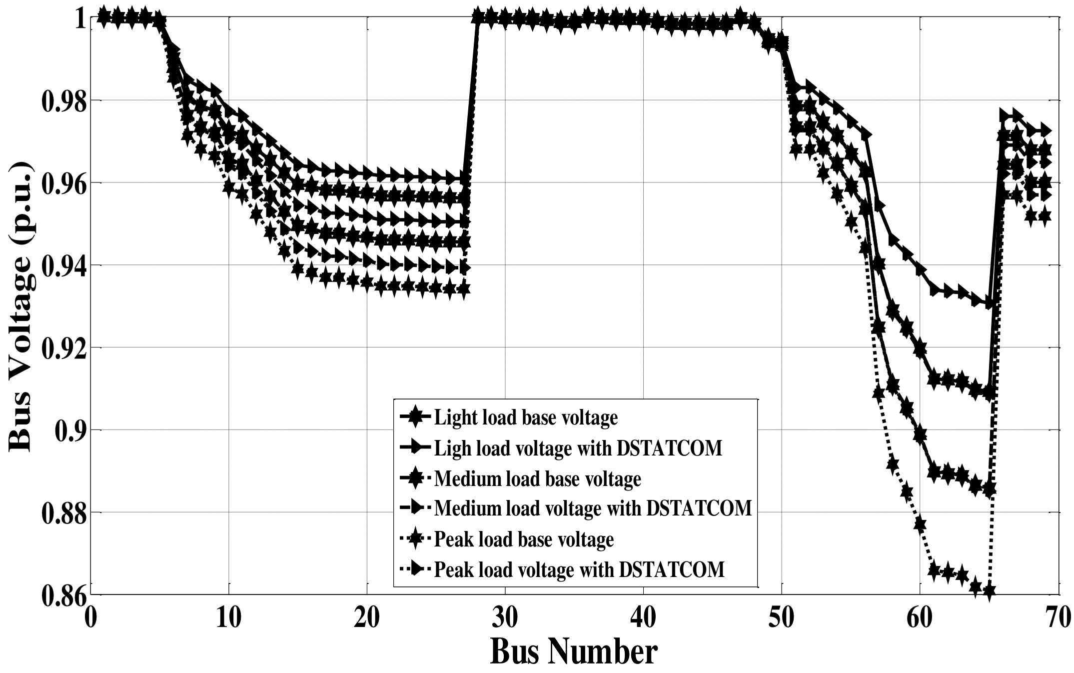

Figure.4.21: Voltage magnitude at various loads with DSTATCOM at bus 61 of IEEE 69-bus distribution network

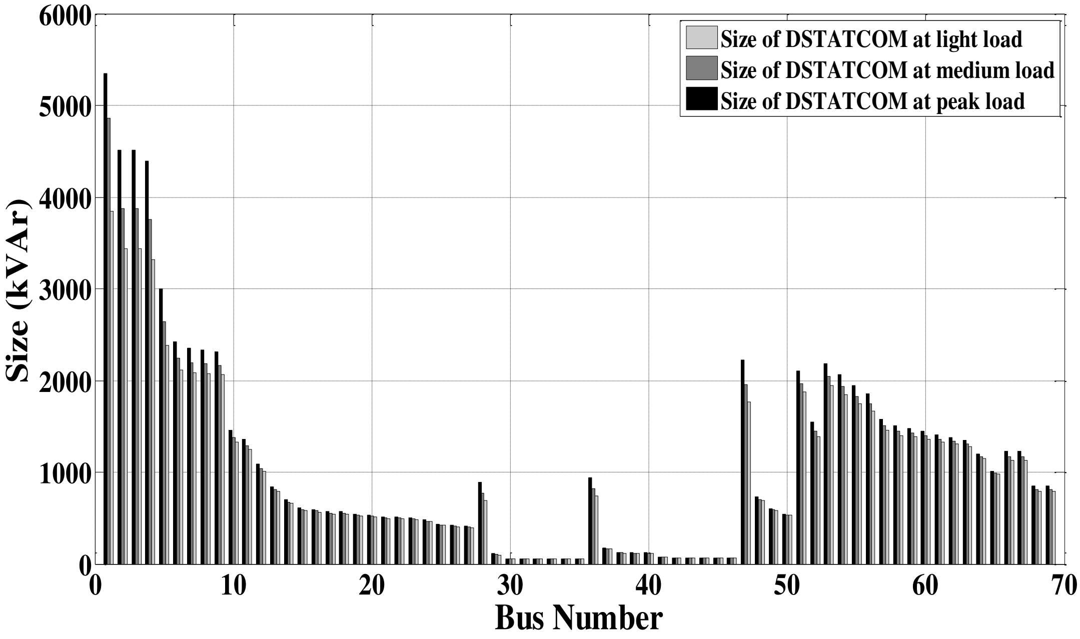

Figure.4.22: Size of DSTATCOM at each bus of IEEE 69-bus distribution network at different loads

4.7.3 Analysis of planning cost

The total planning cost of the all three bus RDNs are described in this section. Table 4.6 shows the comparative results of the total annual planning cost of the RDNs with DSTACOM installation. In the approach of [88] to evaluate the TNP/TCS the planning horizon as shown in Table III is considered only for the evaluation of the DSTATCOM initial capital investment cost (f_{21}) but not for remaining costs such as energy (power) loss cost (f_1), operational and maintenance cost (f_{22} and f_{23}) of the DSTATCOM, so to compare the effectiveness of proposed approach the same scenario is considered along with same PWF which is used in existed approach [88]. As can be seen, compared with IA, DE offers an improved optimal solution with its lower F and higher TNP/TCS. It is noteworthy that the value of F and TNP/TCS are minimized and maximized by 10.5% and 136.18% respectively in the planning of IEEE 33-bus RDN and 8.49% and 61.25% respectively in the planning of IEEE 69-bus RDN using DE compared with IA [88] method. As a result of this approach the TNP/TCS per annum with respect to total energy (power) loss cost without DSTATCOM are valued to be of the order of 17.91%, 16.93% and 19.63%, in 30, 33 and 69 buses RDNs, respectively.

Table 4.8: Comparison of TNP of proposed approach

with the capacitor placement approaches

Test network	Approach	TNP or TCS ($)
33 bus	**IP [119]**	6085
	SA [119]	6183
	GA [120]	10737
	FRCGA 121]	11222
	GSA [119]	12389
	Proposed	26748
69 bus	**IP [119]**	9851
	DE–PS [127]	12052
	GA [120]	12461
	CSA [128]	12653
	DSA [129]	12712
	TLBO [58]	12767
	GSA [119]	12837
	Proposed	35327

Table 4.9: The solution obtained with proposed de algorithm in 50 run considering *PWF* for planning horizon including operational and maintenance cost of DSTATCOM

Test network	Total energy loss cost with DSATCOM (f_1)		Total planning cost (F)	
	Mean ($)	Standard deviation	Mean ($)	Standard deviation
30-bus	599,630	3.8907	606,646	3.9987
33-bus	833,712	4.0253	847,484	4.7672
69-bus	915,495	6.2860	928,017	6.5719

Table 4.7 shows the economic evaluation of total planning cost result per *PH* of RDNs including f_{22} and f_{23} considering the *PWF* as given in Eq. (4.6) and (4.7) in the total planning horizon. As can be seen in both Table 4.7 and Figs. 4.6 and 4.7 there is an obvious rise in TNP/TCS by using proposed approach compared to IA approach [88]. The mean

curves of F obtained by DE in IEEE 30, 33, and 69-bus RDNs are presented in Figs. 4.8, 4.9 and 4.10 respectively. As shown in Table 4.10 the solution convergence takes place in DE after 21st, 25th and 28th generation in 30, 33, and 69-bus RDNs respectively which ascertains that the computational time of proposed algorithm is very faster than the IA, even after 50th iteration. Also, DE has reached a better answer (i.e. lower F and nearer to the global optima) compared with IA and GA. The performance comparison of the TNP with some previous investigations with capacitor allocation has been compared in Table 4.9 and it is observed that the proposed approach with DSTATCOM allocation found better in achieving higher TNP compared to IP, SA, and TLBO [58], GSA[119], GA[120], FRCGA[121], DE-PS[127], CSA[128] and DSA[129].

4.7.4 Analysis of ELC

The total ELC of the all three RDS is described in this section. Table 4.6 shows the comparative results of the total annual ELC of the RDS with DSTATCOM installation scheme. In the approach of [88] to evaluate TNP the whole PH, is considered only for the evaluation of the DSTATCOM initial capital investment cost (f_{21}) but not for remaining costs such as energy (power) loss cost (f_1), operational and maintenance cost (f_{22} and f_{23}) of the DSTATCOM, so to compare the effectiveness of proposed approach the same scenario is considered along with same PWF which is used in existed approach [88]. As can be seen, compared with IA, DEA offers an improved optimal solution with its lower F and higher TNP.

Table 4.10: Comparison of convergence of mean curve of F

Test network	Approach	Convergence of F occurred	CPU Time(s)
30-bus	**Proposed**	After 21st generation	175.38
	IA [88]	--	--
33-bus	**Proposed**	After 25th generation	200.02
	IA [88]	After 50th generation	21,220
	GA [88]	After 75th generation	24,157
69-bus	**Proposed**	After 28th generation	789.25
	IA [88]	After 50th generation	32,305
	GA [88]	--	45,588

It is noteworthy that the value of *F* and TNP are minimized and maximized by 10.5% and 136.18% respectively in the scheme of IEEE 33-bus DN and 8.49% and 61.25% respectively in the scheme of IEEE 69-bus DN using DEA compared with IA [88] method. As a result of this approach the TNP per annum with respect to total ELC with DSTATCOM are valued to be of the order of 17.91%, 16.93%, and 19.63%, in 30, 33 and 69 buses DN, respectively. Similarly, for the total PH of DSTATCOM installation scheme (30 years), 22.88%, 20.39%, and 22.90% of TNP has been achieved by proposed approach in 30, 33 and 69 bus system respectively as shown in "Tables 4.7" which is quite profitable and useful for "DISCOs" (distribution companies).

4.8 Conclusion

This paper presents optimization of total ELC of DS with DSTATCOM allocation. In this scheme minimization of P_{loss}, improvement in voltage profile, minimization of ELC and installation cost of the DSTATCOM and, the maximization of TNP are obtained by sizing and allocating the DSTATCOM optimally in RDS using DEA. The objective function is defined by using energy losses and its associated cost after the installation of DSTATCOM. Forward- backward sweep load flow algorithm is used for the solution of the network. Simulation results show that the objective function is optimized with DSTATCOM using DEA. Compared with IA, DEA technique offers minimum power loss, CPU time, objective function and maximum TNP. The reduction in total ELC after the installation of DSTATCOM by the proposed approach for the whole PH of DSTATCOM installation scheme leads to 23.86%, 21.14% and 23.61% in 30, 33 and 69 buses DN, respectively. TNP as a result of this approach is valued to be of the order of 22.88%, 20.39%, and 22.90%, in 30, 33 and 69 buses DN, respectively. The simulation results in Table 4.5, and 4.7 of proposed work are found better compared to [88] and [119]. The voltage at each bus and current in each line are within the permissible boundaries. This is all about the allocation of single DSTATCOM in RDS. However, the next chapter investigates and describes what happens to the system power loss and bus voltage if the reactive power is compensated by the multiple DSTATCOMs and the combination of DSTATCOM and DG.

Appendix:

Tables A and B show the line and bus data of 33 and 69 bus radial distribution systems under light load condition. Medium load condition is considered as the sum of light load and 30% of light load. Peak load condition is considered as the sum of light load and 60% of the light load according to the reference [88]. The three load conditions have been considered from reference [88] since the simulation results of proposed approach in this chapter has been compered mainly with the ref [88].

Table A: Data of 33 bus RDS

Bus		Line Data		Bus Data	
Send	Receive	Line Resistance (Ω)	Line Reactance (Ω)	Active Load power (kW)	Reactive Load power (kVAr)
1	2	0.0922	0.0470	100	60
2	3	0.4930	0.2511	90	40
3	4	0.3660	0.1864	120	80
4	5	0.3811	0.1941	60	30
5	6	0.8190	0.7070	60	20
6	7	0.1872	0.6188	200	100
7	8	0.7114	0.2351	200	100
8	9	1.0300	0.7400	60	20
9	10	1.0440	0.7400	60	20
10	11	0.1966	0.0650	45	30
11	12	0.3744	0.1238	60	35
12	13	1.4680	1.1550	60	35
13	14	0.5416	0.7129	120	80
14	15	0.5910	0.5260	60	10
15	16	0.7463	0.5450	60	20
16	17	1.2890	1.7210	60	20
17	18	0.7320	0.5740	90	40
2	19	0.1640	0.1565	90	40
19	20	1.5042	1.3554	90	40
20	21	0.4095	0.4784	90	40
21	22	0.7089	0.9373	90	40
3	23	0.4512	0.3083	90	50
23	24	0.8980	0.7091	420	200
24	25	0.8960	0.7011	420	200
6	26	0.2030	0.1034	60	25
26	27	0.2842	0.1447	60	25
27	28	1.0590	0.9337	60	20
28	29	0.8042	0.7006	120	70
29	30	0.5075	0.2585	200	600
30	31	0.9744	0.9630	150	70
31	32	0.3105	0.3619	210	100
32	33	0.3410	0.5302	60	40

Table B: Data of 369 bus RDS

Bus		Line Data		Bus Data	
Send	Receive	Line Resistance (Ω)	Line Reactance (Ω)	Active Load power (kW)	Reactive Load power (kVAr)
1	2	0.0005	0.0012	0	0
2	3	0.0005	0.0012	0	0
3	4	0.0015	0.0036	0	0
4	5	0.0251	0.0294	0	0
5	6	0.366	0.1864	2.6	2.2
6	7	0.3811	0.1941	40.4	30
7	8	0.0922	0.047	75	54
8	9	0.0493	0.0251	30	22
9	10	0.819	0.2707	28	19
10	11	0.1872	0.0691	145	104
11	12	0.7114	0.2351	145	104
12	13	1.03	0.34	8	5.5
13	14	1.044	0.345	8	5.5
14	15	1.058	0.3496	0	0
15	16	0.1966	0.065	45.5	30
16	17	0.3744	0.1238	60	35
17	18	0.0047	0.0016	60	35
18	19	0.3276	0.1083	0	0
19	20	0.2106	0.0696	1	0.6
20	21	0.3416	0.1129	114	81
21	22	0.014	0.0046	5.3	3.5
22	23	0.1591	0.0526	0	0
23	24	0.3463	0.1145	28	20
24	25	0.7488	0.2745	0	0
25	26	0.3089	0.1021	14	10
26	27	0.1732	0.0572	14	10
3	28	0.0044	0.0108	26	18.6
28	29	0.064	0.1565	26	18.6
29	30	0.3978	0.1315	0	0
30	31	0.0702	0.0232	0	0
31	32	0.351	0.116	0	0
32	33	0.839	0.2816	14	10
33	34	1.708	0.5646	19.5	14
34	35	1.474	0.4873	6	4
3	36	0.0044	0.0108	26	18.55
36	37	0.064	0.1565	26	18.55
37	38	0.1053	0.123	0	0
38	39	0.0304	0.0355	24	17
39	40	0.0018	0.0021	24	17
40	41	0.7283	0.8509	1.2	1
41	42	0.31	0.3623	0	0
42	43	0.041	0.0478	6	4.3
43	44	0.0092	0.0116	0	0
44	45	0.1089	0.1373	39.22	26.3
45	46	0.0009	0.0012	39.22	26.3
4	47	0.0034	0.0084	0	0

47	48	0.0851	0.2083	79	56.4
48	49	0.2898	0.7091	384.7	274.5
49	50	0.0822	0.2011	384.7	274.5
8	51	0.0928	0.0473	40.5	28.3
51	52	0.3319	0.1114	3.6	2.7
9	53	0.174	0.0886	4.35	3.5
53	54	0.203	0.1034	26.4	19
54	55	0.2842	0.1447	24	17.2
55	56	0.2813	0.1433	0	0
56	57	1.59	0.5337	0	0
57	58	0.7837	0.263	0	0
58	59	0.3042	0.1006	100	72
59	60	0.3861	0.1172	0	0
60	61	0.5075	0.2585	1244	888
61	62	0.0974	0.0496	32	23
62	63	0.145	0.0738	0	0
63	64	0.7105	0.3619	227	162
64	65	1.041	0.5302	59	42
11	66	0.2012	0.0611	18	13
66	67	0.0047	0.0014	18	13
12	68	0.7394	0.2444	28	20
68	69	0.0047	0.0016	28	20

Chapter 5

Optimal Phase Angle injection for Reactive Power Compensation of Distribution Systems with the Allocation of Multiple DSTATCOM and DG

5.1. Introduction

In this chapter, the allocation of optimal phase angle model of multiple distribution STATCOM (DSTATCOM) and the combination of both DSTATCOM and DG (distributed generation) in RDS for the optimal reactive power compensation is presented. The objective function used in this approach is same as that of the objective function used in chapter 3, which is Eq. (3.1). The optimal location(s), optimal phase angle(s), and rating(s) for DSTATCOM and DG, are determined based on the best reduction in minimum power loss of radial distribution systems (RDS). The role of DSTATCOM in this chapter is injecting reactive power and the role of DG is injecting active power in to the RDS. Firstly, the impact of multiple DSTATCOM allocation on system power loss and voltage have been studied. Secondly, the impact of combination of single DSTATCOM and DG allocation on RDS have been studied.

5.2. Multiple DSTATCOM allocation

In this section, the new modeling of DSTATCOM developed in chapter 2 is allocated in multiples of single DSTATCOM in RDS to compensate the reactive power. Multiple DSTATCOMs are suitably incorporated in the forward-backward sweep (FBS) load flow algorithm in the same manner discussed in chapter 2 so as to determine the line currents, node voltages and the power loss of RDS. Differential evolution (DE) algorithm is used as the optimal solution scheme for the optimization of the power loss. The 69-bus RDS is used to validate the efficacy of the proposed approach. The results demonstrate that the proposed technique is more effective in compensating the reactive power to reduce the power loss compared to some of the previous approaches.

As discussed in chapter 1.2 the previous studies investigated that the higher reduction of power loss is possible with simultaneous use of different reactive power compensation techniques, for example, DSTATCOM allocation along with network reconfiguration, DG placement with network reconfiguration, DSTATCOM placement for supplying reactive power to the DG units, a combination of DVR (dynamic voltage restorer) and D-STATCOM etc. However, there are certain problems with the use of combinatorial devices and methods. The combination of optimal operation and network reconfiguration of the distribution system is a complicated problem since the network reconfiguration results in a change in topology of feeder structure by opening or closing of sectionalizes. Moreover, the control of DSTATCOM with DG in the distribution systems is complex, and a DVR is costlier as compared to a DSTATCOM. In view of all these difficulties, it is interesting to investigate the impact of optimal allocation of multiple DSTATCOM in RDS.

5.2.1. Proposed Solution Strategy Using DE

The parameter values and optimal problem variables for this case are mentioned in Table. 5.1. A typical string structure is shown in Fig. 5.1 used in this approach. The dimension of each string is seven in this approach. The first variable N_{DSTAT} in the string represents the number of DSTATCOMs considered in the string. The DSTATCOM 1, DSTATCOM 2, and DSTATCOM 3 in the string are represented by the variables n_1, n_2, and n_3 respectively. The corresponding phase angle variables of DSTATCOMs are represented by $\beta'_{n+1,n1}$, $\beta'_{n+1,n1}$, and $\beta'_{n+1,n1}$. The locations for DSTATCOM are engaged in the same manner of the approach in chapter 3. Multiple DSTATCOMs are allocated one at a time at all the nodes except the substation node the range of the angle β'_{n+1} lies in between 0 to 90 degrees. The DEA discussed in chapter 3 is the solution strategy in this approach to optimize the locations and sizes for the DSTATCOM in RDS in order to optimize the power loss and voltage profile.

Table 5.1: Parameters of DE algorithm

N_P	*D*	*F*	*CR*	*Generations*
50	7	0.7	0.8	100

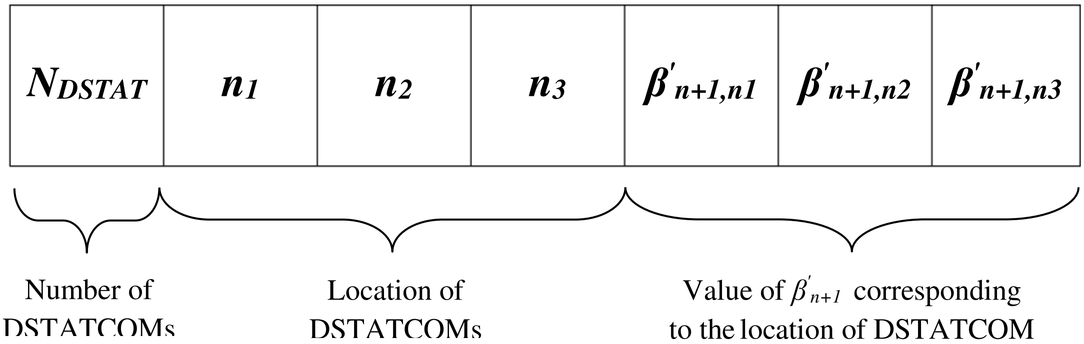

Figure.5.1: A typical string for DE

5.2.2. Simulation Results

In this section, the simulation results are presented to show the impact of the allocations of multiple DSTATCOM in the network in minimizing the power loss. To alleviate the effectiveness of the proposed approach a 69 bus RDS is considered as the test system. The data of 69 bus RDS is taken from the 'appendix B' in 4^{th} chapter. The active and reactive power loss of the system before the installation of DSTATCOM(s) are 224.98 kW and 102.1kVAr respectively. The simulation results obtained with the allocation two DSTATCOMs proposed work have been compared with BFOA approach [130] and reconfiguration and DSTATCOM allocation scheme [57] in Table 5.2. The Table 5.3 provides the reactive power compensation in RDS using multiple DSTATCOMs i.e. allocation of three, four, five and six combinations of DSTATCOM in RDS. To simplify the explanation of the proposed approach in this section has been considered as different cases operations and each combination is named with a case number as follows:

- Case-1: Allocation of two DSTATCOMs
- Case-2: Allocation of three DSTATCOMs
- Case-3: Allocation of four DSTATCOMs
- Case-4: Allocation of five DSTATCOMs
- Case-5: Allocation of six DSTATCOMs

5.2.2.1. Results of Multiple-DSTATCOM allocation using DE

This section explains the simulation results of DEA based multiple DSTATCOM approach. The minimum power loss corresponding to the best solution in each generation with multiple DSTATCOM allocation is shown in Fig. 5.2. The mean power loss of the population in each generation is shown in Fig. 5.3. The optimal locations and sizes for the DSTATCOM are given in Table 5.2. The minimum power loss is found to be 146.4kW with the 31.52° and 42.24° of optimal phase angles injection by the DSTATCOMs at buses 17, 61 respectively. The corresponding rating of DSTATCOM 1, and DSTATCOM 2 are 361.1 kVAr and 1275.1 respectively. Fig. 5.4 represents the voltage profile of the RDS before and after the allocation of multiple DSTATCOMs i.e. two DSTATCOMs. Before the installation DSTATCOMs, the minimum voltage of the system is recorded as 0.9092 *p. u.* and after the installation of multiple DSTATCOMs, it has been improved to 0.9312 *p. u.* The voltage profile of the systems is improved by 2.41% with the proposed approach. The voltage profile is the main parameter to maintain properly at each moment in the RDS since RDS delivers the power to the consumers.

Table 5.2: Comparative results of multiple DSTATCOMs allocation

Parameter	Base Case	Ref [57] - DSTATCOM with reconfiguration (Example-1, Case-4)	Ref [130] BFOA	Proposed Approach with two DSTATCOMs (Case-1)
Optimal phase angle (β'_{n+1})	--	--	--	31.52°
		--	--	42.24°
Optimal sizes (kVAr) and locations	--	Reconfiguration	480(15)	361.1(17)
		2680(61)	1430(61)	1275.1(61)
Total kVAr	--	2680	1910	1636
Power loss (kW)	224.9	137.49	148.0	146.4
% Reduction in power loss	--	38.8	34.1	35.0
Reactive power loss (kVAr)	102.1	128.74	68.7	68.2
% Reduction in reactive power loss	--	-26.1	32.7	33.2
Minimum voltage	0.9092	--	--	0.9312

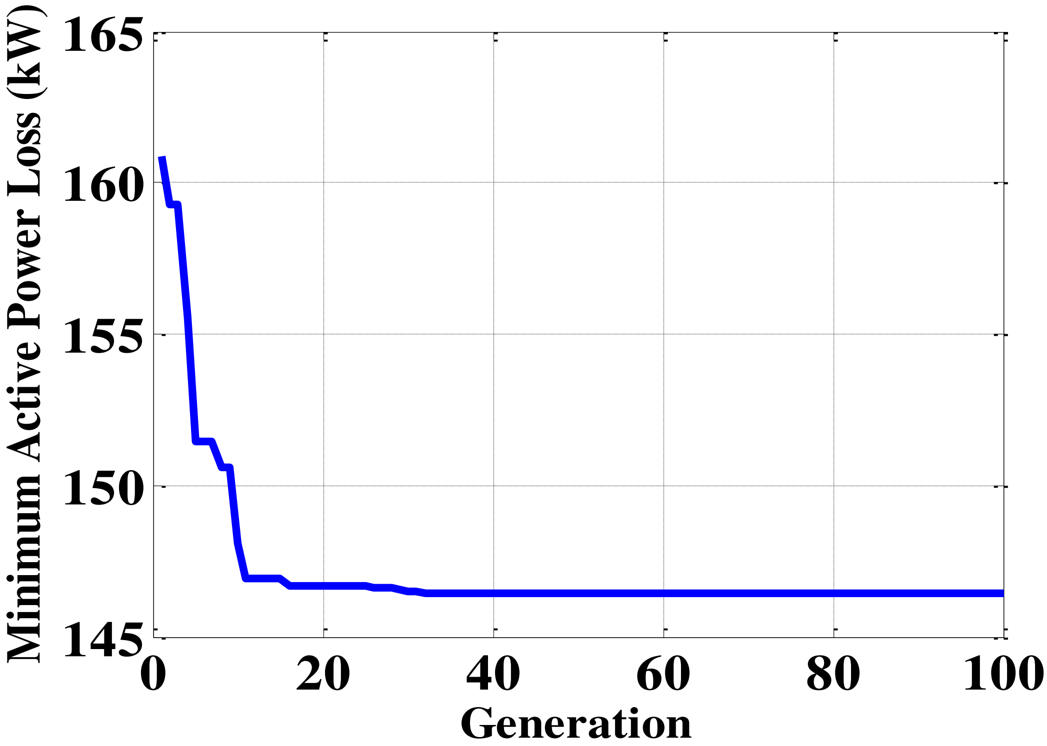

Figure.5.2: Power loss corresponding to the best solution with multiple DSTATCOM allocation

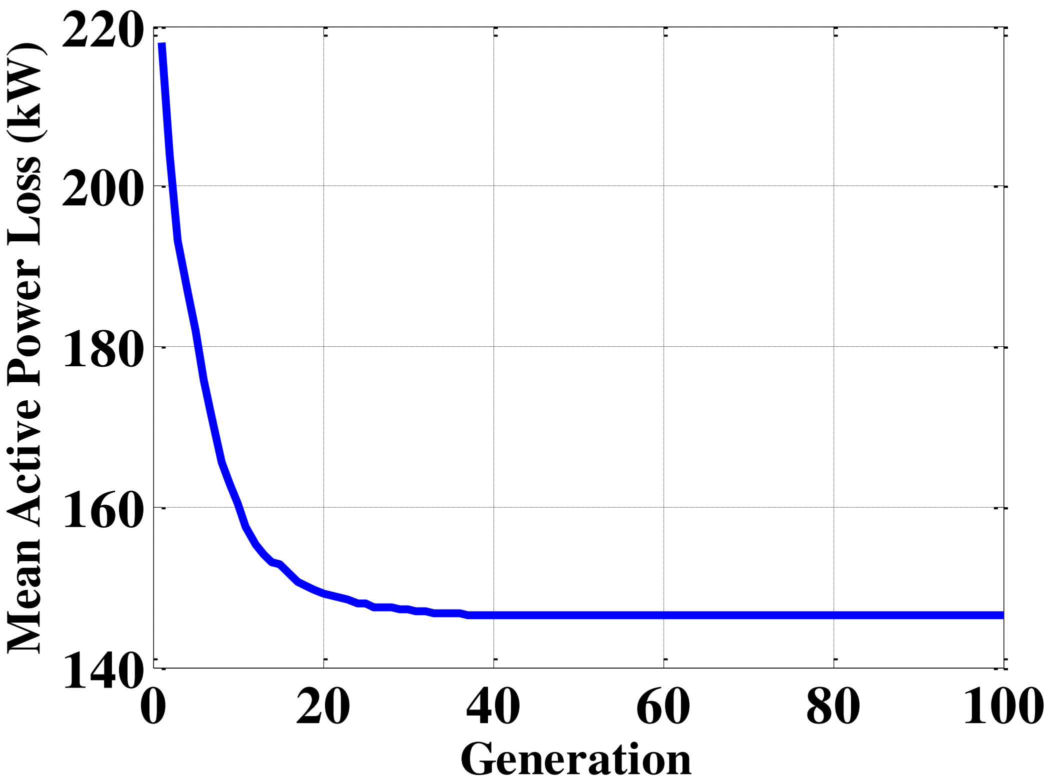

Figure.5.3: Mean power loss of each generation with multiple DSTATCOM allocation

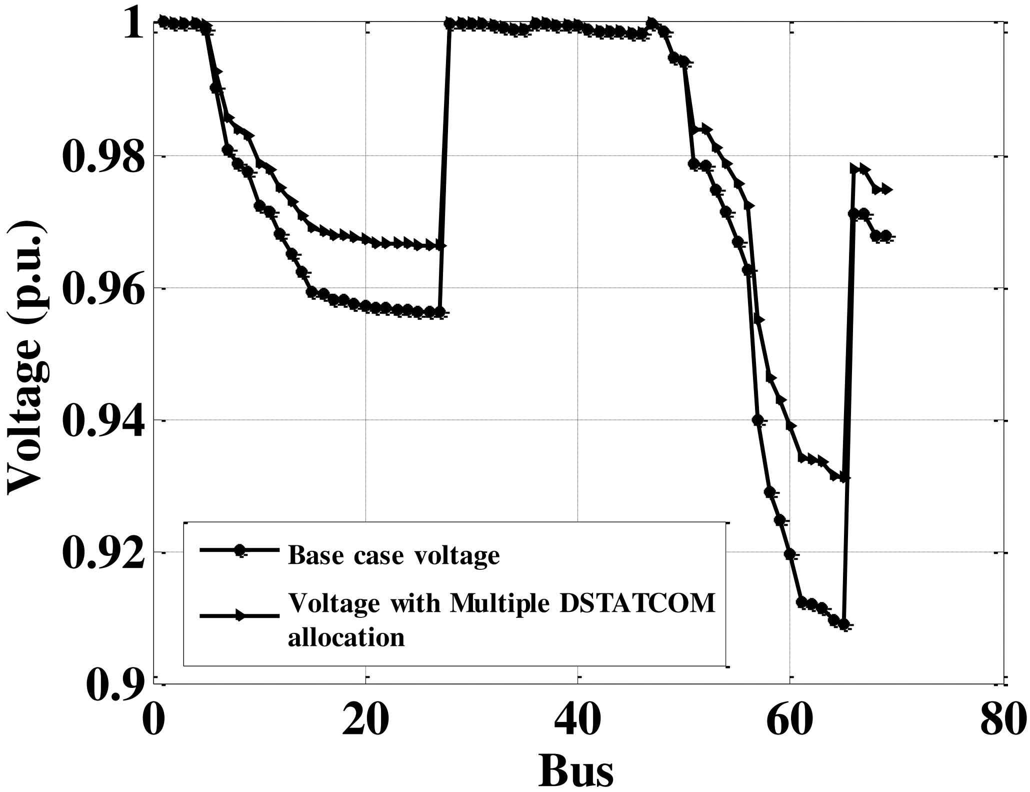

Figure.5.4: Voltage profile with and without allocation of multiple DSTATCOM

5.2.2.2. Comparative results with some of the previous works

Table 5.2 shows the comparison of power loss with previous methods in reducing the power loss of 69-bus RDS when the combinatorial devices are allocated to the system. In the proposed approach the active and reactive power loss of the network are found to be 146.4 kW and 68.2 kVAr when two DSTATCOMs(case-1) are optimally placed in the system simultaneously in the locations 17, and 61 with 31.52°, and 42.24° of optimal phase angle injection respectively. The active and reactive power loss are reduced by 35.0% and 33.2% respectively in the proposed approach, whereas, in BFOA approach the active and reactive power loss are reduced by 34.1% and 32.7% respectively with the placement of two DSTATCOMs in different locations respectively. In ref [57], 38.8% of power loss are reduced with DSTATCOM and reconfiguration technique. However, the size of the DSTATCOM is very high compared to the total optimal size of multiple DSTATCOM in the proposed approach. Moreover, the reactive power loss are increased by 26.1% (-26.1%) compared to base case reactive power loss. As discussed in section '1.2 in chapter

1' the allocation of DSTATCOM and reconfiguration in RDS has several dis advantages such as high switching losses, control complexity and expensive compared to the proposed approach. The injection of phase angle at a particular location in the network has a best and immaculate impact on the reduction in active power loss compared to the concrete injection of reactive power, which was preferred in previous investigations to reduce the power loss. From this analysis, one can conclude that the proposed approach i.e. the idea of optimal phase angle injection to compensate the reactive power in RDS with the optimal allocation of two-DSTATCOM in RDS is useful and effective to reduce the power loss significantly.

Table 5.3: Reactive power compensation of RDS with the optimal allocation of multiple DSTATCOMs using DEA

Parameter	**Proposed approach**			
	Allocation of three DSTATCOMs (Case-2)	**Allocation of four DSTATCOMs (Case-3)**	**Allocation of five DSTATCOMs (Case-4)**	**Allocation of six DSTATCOMs (Case-5)**
Optimal sizes (kVAr) and locations	267.5(18), 339.9(66), 1239.6(61)	351.7 (18), 268.2 (67). 759.2 (50), 1246.7 (61)	1285.5(61), 388.8(5), 193.9(22), 89.5(12), 247.1(8)	380.63(66), 322.3(19), 779.2(50), 367.8(5), 254.4(36), 1229.5(61)
Total kVAr	1847	2625.8	2204.8	3333.8
P_{loss} **(kW)**	145.2	144.9	145.6	144.9
% Reduction in P_{loss}	35.4	35.6	35.2	35.5
Q_{loss} **(kVAr)**	67.7	66.3	67.8	66.4
% Reduction in Q_{loss}	33.7	35.0	33.6	34.9
Minimum voltage	0.9314	0.9394	0.9319	0.9317

The simulation results obtained in the reactive power compensation in 69-bus RDS with the allocation of three and more than three multiple DSTATCOMs are provided in Table 5.3. Not only the case-1 given in Table 5.2 but the case-2 operation also provides the best results compared to the previous investigations in ref [57] and BFOA approaches with little increased rating of total kVAr. The case-2 operation causes the power loss to be reduced to 145.2kW with the total reactive power of 1847 kVAr. It is observed that case-5 also causes almost the same active power reduction when it is compared with case-2 but with different amount of kVAr. Similarly, case-3 and case-5 operation causes the same active power loss reduction but with the different amount of kVAr. In all cases from case-2 to case-5 there is no much variation in reduction of power loss even though the number of DSTATCOMs allocation is increased rather the total kVAr required is increased. At this stage, the planning cost of the multiple DSTATCOM installation scheme shall be uneconomical and not profitable. From this analysis, one can easily understand that the allocation of three or more than three DSTATCOMs in RDS is an expensive scheme and preferable. Hence, the author has focused on the allocation of DSTATCOM and DG (distribution generation) in RDS to compensate the reactive power. The combination of both DSTATCOM and DG allocation scheme is investigated in the following section 5.3.

5.3. Allocation of DSTATCOM and DG

This section contributes the optimal allocation of DSTATCOM and DG in radial distribution systems using ESM to reduce the power loss and improvement of the voltage profile. The certain range of active and reactive powers have been injected simultaneously at each node by incorporating the corresponding size of DSTATCOMs and DGs respectively into the radial distribution system (RDS). On the basis of best reduction in power loss, the Size of DSTATCOM and DG are determined. FBS load flow algorithm provided in chapter 2 was used for the load flow solutions. The results obtained by proposed approach shows the optimal allocation and sizing of DSTATCOM and DG in RDS efficaciously reduces the power loss and improves the voltage profile compared to the results obtained with the three or more than three DSTATCOM allocation approach provided in previous section in this chapter. The IEEE-30bus RDS was used as a test system.

5.3.1. Importance of DSTATCOM and DG allocation in RDS

The demand on the utilization of electricity is getting increased day by day at the end of the distribution system. To meet the demand, the concept of real and reactive power compensation is required to be considered in RDS. Injection of real power and compensation of reactive power in RDS causes the reduction in total power loss and improvement in the voltage profile [131]. The real power can be generated by using DG, so DG's are also called as the small-scale electricity generators that have become more prevalent in the present day scenario [87]. The allocation of DG in RDS reduces the power loss and improves the voltage profile thereby providing the energy security, reduction in the emission of greenhouse gas [116] and the deregulation of electricity market [117]. The optimal allocation and the sizing of DG to reduce the power loss using analytical method was proposed in [118]. The authors of [119] and [120] have proposed the optimal allocation of multiple DG's for the reduction of power loss and mitigation of the voltage problems to improve the efficiency of the system thereby achieving cost profit. However, the main functioning of DG is generating the active power thus behaving like a real power source but not reactive power compensator [121]. Hence, the proposed approach in this chapter consider a DG along with DSTATCOM to compensate the reactive power in RDS.

5.3.2. Problem Formulation

A simple distribution system has a line connected between two nodes i, i+1. It is considered that there is a load connected at each node. The line real and reactive power loss between two buses i, i+1 can be evaluated by the following Eq. (5.1) and (5.2)

$$P_{loss}^{i,i+1} = \frac{P_i^2 + Q_i^2}{\left|v_i^2\right|} \times R_{line}^{i,i+1} \tag{5.1}$$

$$Q_{loss}^{i,i+1} = \frac{P_i^2 + Q_i^2}{\left|v_i^2\right|} \times X_{line}^{i,i+1} \tag{5.2}$$

The real and reactive power was injected at node i/i+1 by the allocation of DG and DSTATCOM respectively, then the total power loss in the system can be evaluated by the following Eq. (5.3)

$$P_{loss}^{with\ DG\ and\ DSTATCOM} = \sum_{i=1}^{n-1} I_{line}^2 \times R_{line} \tag{5.3}$$

$$I_{line} = I_{load} + I_{DSTATCOM}^{DG} \tag{5.4}$$

$$I_{DSTATCOM}^{DG} = \frac{P_{DG} + jQ_{DSTATCOM}}{\overline{V}'_{i,i+1}} \tag{5.5}$$

The % reduction in power loss after the allocation of both DSTATCOM and DG is defined as "the ratio of power loss after and before the allocation of DSTATCOM and DG" and it expressed by the Eq. (5.6).

$$P_{loss}^{total} = \frac{P_{loss}^{with\ DG\ and\ DSTATCOM}}{P_{loss}^{without\ DG\ and\ DSTATCOM}} \times 100 \tag{5.6}$$

5.3.3. Integration of DSTATCOM and DG

The sizes of the both DSTATCOM and DG are chosen between the range of 1 to 2000 kW and kVAr respectively per each division of abscissa. At each node both devices are allocated simultaneously in an incremental mental way using the ESM algorithm provided in chapter 3, section 3.2.2. At the value of each division of abscissa, there is a certain change in the power loss of the system. In addition, it is observed that ESM algorithm found an optimal reduction in the power loss and improvement in voltage profile in RDS at the end of final iteration with the integration of optimal size of DSTATCOM and DG at particular nodes. Generally, Distribution systems suffer from high power loss due to high R/X ratio, so the traditional load flow studies such as Newton-Raphson method, Gauss-Seidel and fast-decoupled methods cannot be used to find the load flows and voltages in RDS. There are several load flow techniques have been proposed by researchers for distributions systems [132-134]. In this approach, forward-backward load flow algorithm provided in chapter 2 is used for the load flow solutions. Table 5.4 described the algorithm developed for the allocation of DSTATCOM and DG. Fig. 5.5 shows a generalized flow chart of forward-backward sweep algorithm integrating the DSTATCOM and DG in ESM algorithm. In this approach both ESM and FBS, algorithms have considered the injection of active power also by using DG. Hence, in 7th line of algorithm it can be seen that the Q_{DG} is injected into the active load power of the RDS. So, it is reflected in load current evaluation.

Table.5.4: ESM Algorithm for the allocation of DSTATCOM and DG:

Require: Initialization of accuracy; maxiter; no. of nodes;

Require: Read the bus data and line data

Require: Create dummy matrices mat, V, X, and Rosh with required sizes in zeros/ones

```
for location=1:n
   for cap=1:1:pahse angle or specified maximum limit of Q_DSTATCOM and Q_DG rating
      for iter=1:maxiter
         for j=n:-1:2
          Ij=conj (complex(s (j, 1)-Q_DG, s (j, 2)-Q_DSTATCOM)/V (1, j));
             while (j<=n)
               count=0;
               if (count==1)
               end node = j;
               elseif (count==2)
            end
            break
        end
     end
if (max (abs (DIF))<=accuracy)  %( check convergence)%
break
end
end
P loss /Q loss =0;
for b=1:n-1
   Evaluate (P loss /Q loss)
end
Rosh (location, cap) = P loss /Q loss;
end
end
Print size of DSTATCOM; Plot minimum P loss /Q loss and voltage;
```

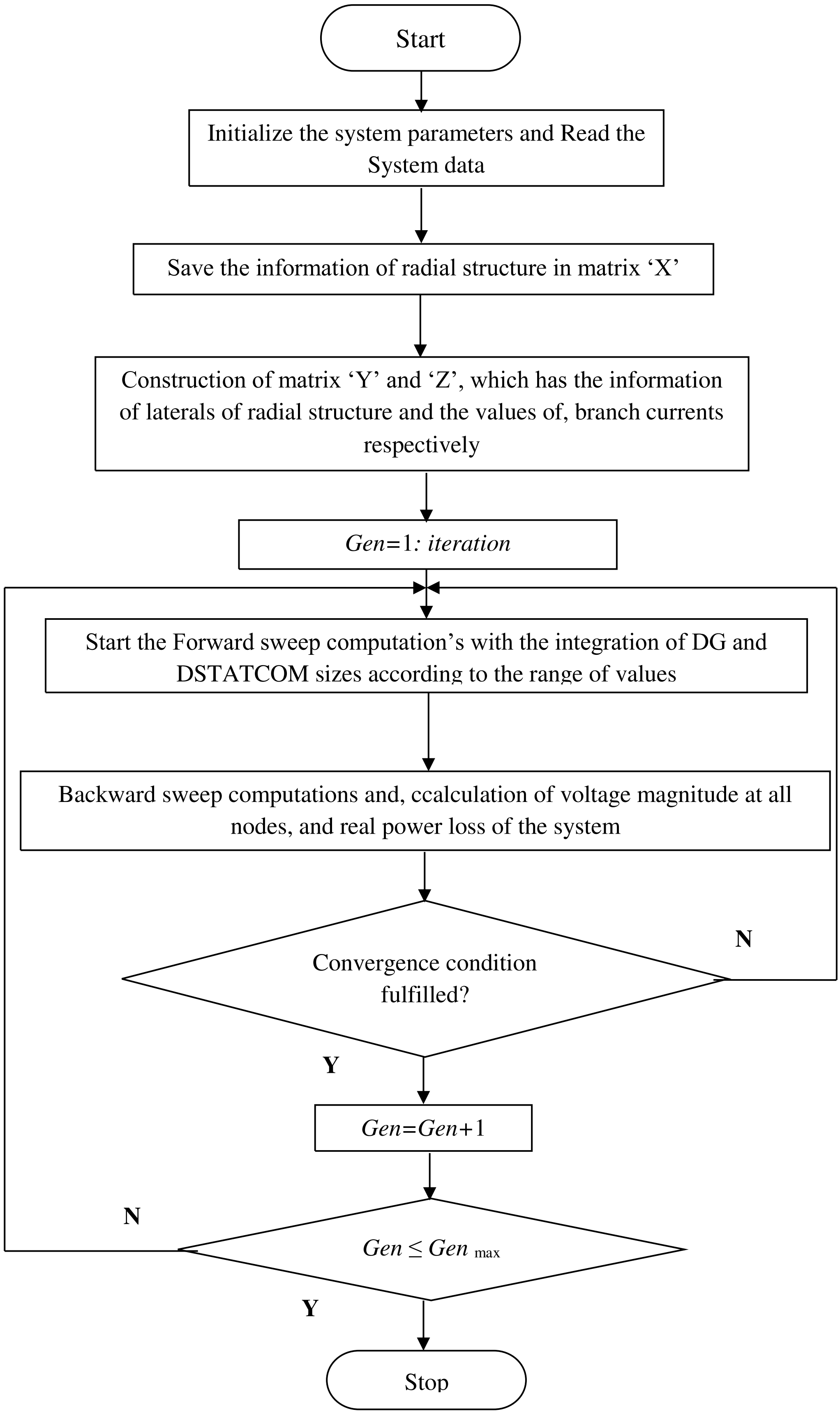

Figure.5.5: Flow chart of load flow algorithm with ESM

5.3.4. Analysis of Simulation Results

To evaluate the proposed work the 11kV, 100MVA, IEEE 30-node RDS has been considered [135] and [136]. The accuracy of convergence criteria has been considered as 10^{-3}. The simulation results are not compared with any previous investigations since no work has considered IEEE 30-bus RDS for the allocation of DSTATCOM and DG. However, the simulation results obtained in this approach say that this approach is useful to implement practically in DISCOs to compensate the reactive power to improve the power quality of the customer.

Table 5.5: Results obtained after the allocation of single DSTATCOM or DG

Parameter		Operational aspect		
		Without DSTATCOM	**With Single DSTATCOM at node-5**	**With Single DG at Node-5**
Size	**kVAr**	--	1152	--
	kW	--	--	1537
Active Power loss (kW)		147.2	101.4	67.14
Reactive Power Loss (kVA)		89.9	59.5	36.7
Minimum node voltage (p.u.)		0.9046	0.9303	0.9546
Active Power loss reduction (%)		00.00	31.01	54.38

Table 5.6: Results obtained with the allocation of DG and DSTATCOM simultaneously

Operational aspect	**Same location**	**Different location**
Node number for DG allocation	5	11
Node number for DSTATCOM allocation	5	5
Size of DG (kW)	1413	815
Size of DSTATCOM (kVAr)	1152	1152
Active power loss(kW)	28.88	46.4
Reactive power loss (kVA)	11.3	22.5
Minimum node voltage(p.u.)	0.9740	0.9548
Active power loss reduction (%)	80.38	68.47

5.3.4.1. Power loss reduction

Fig.5.6 shows power loss reduction with the different sizes of DSTATCOM and DG from 1 to 2000 kW and kVAr respectively at all nodes of RDS. Also from Fig.5.6 it is clear that the maximum feasible reduction in power loss was achieved, at a particular location with the certain size of DSTATCOM/DG. As mentioned in Table 5.5 the base case power loss of the system i.e. 147.2 kW was reduced to 67.14 kW and 101.4 kW when the 1537 kW size of DG and 1152 kVAr size of DSTATCOM are respectively allocated at node-5 individually alone.

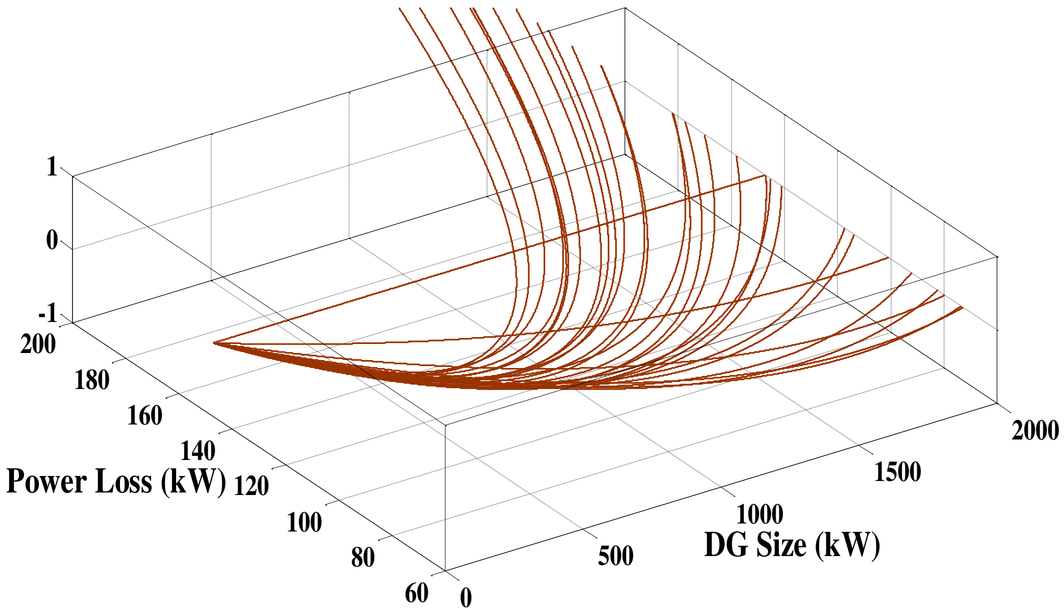

Figure: 5.6: Variation of power loss with increment of DG size in each node

Table 5.5, and Fig.5.7 show that the allocation of DG causes a better reduction in power loss and improvement in voltage profile compared to the allocation of DSTATCOM in RDS. Fig.5.8 describes the various sizes of DSTATCOM and DG corresponding to the minimum power loss. It is observed that the sizes of DG compared to DSTATCOM are higher at all times to reduce the power loss when they are allocated in the system individually alone. Normally, the cost of DG is higher than the DSTATCOM, so it is an interest to allocate the DSTATCOM and DG together simultaneously in the system so as to reduce the size and cost of DG to achieve the maximum possible reduction in power loss and improvement in voltage profile. Table 5.6 shows the comparison of reduction in the power loss when the allocation DSTATCOM and DG locations have been changed. There is quite reduction in the size of the DG when DSTATCOM and DG have been allocated at different locations. There is a significant improvement of voltage profile when DSTATCOM and DG are allocated in the system simultaneously as shown Fig.5.9.

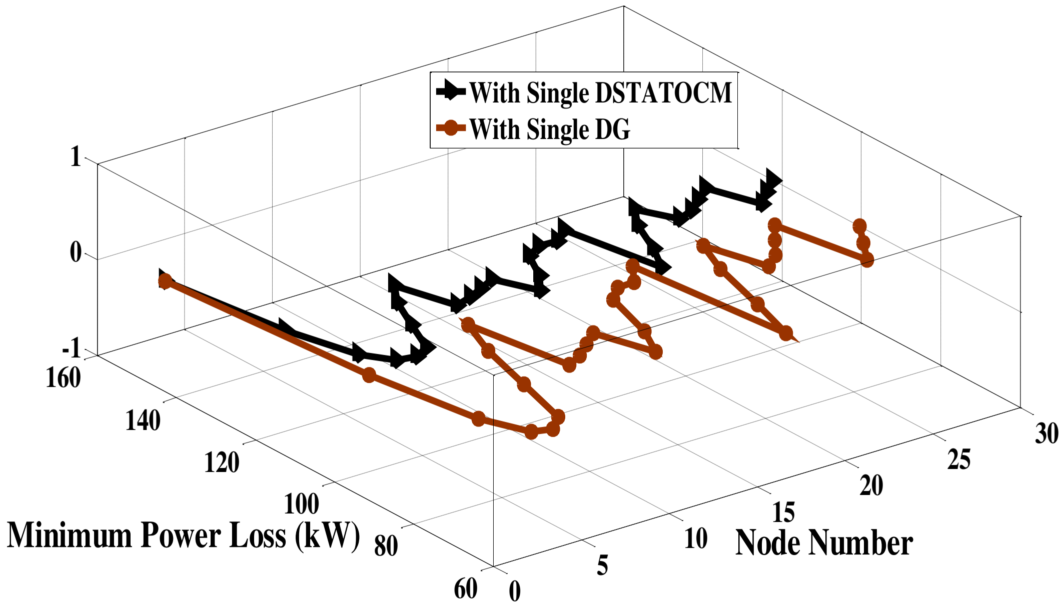

Figure: 5.7: Minimum power loss in each node due to integration of DSTATCOM or DG

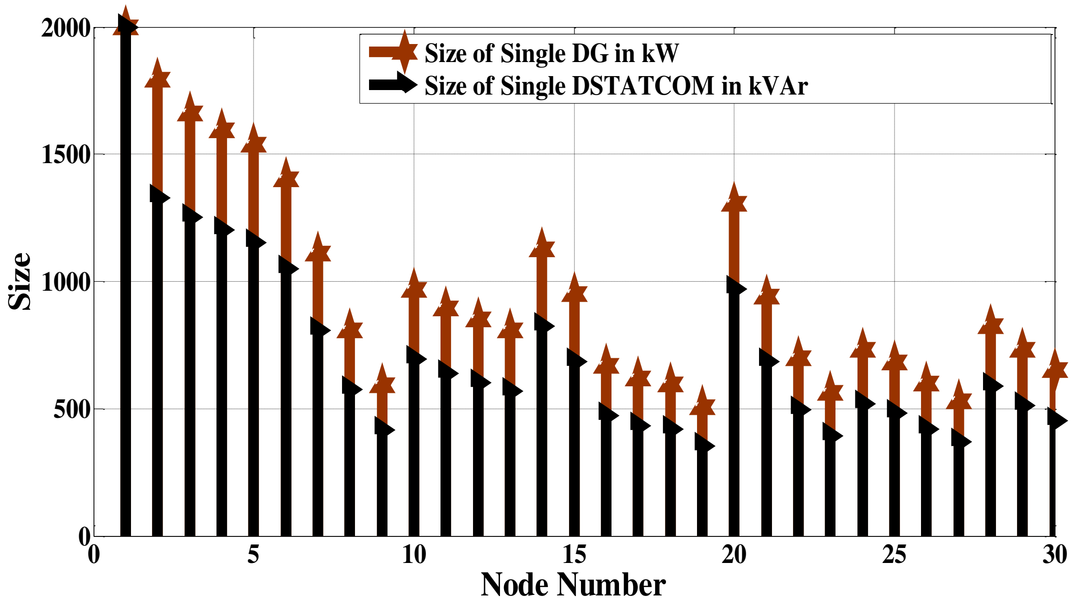

Fig. 5.8: DSTATCOM or DG size corresponding to minimum power loss

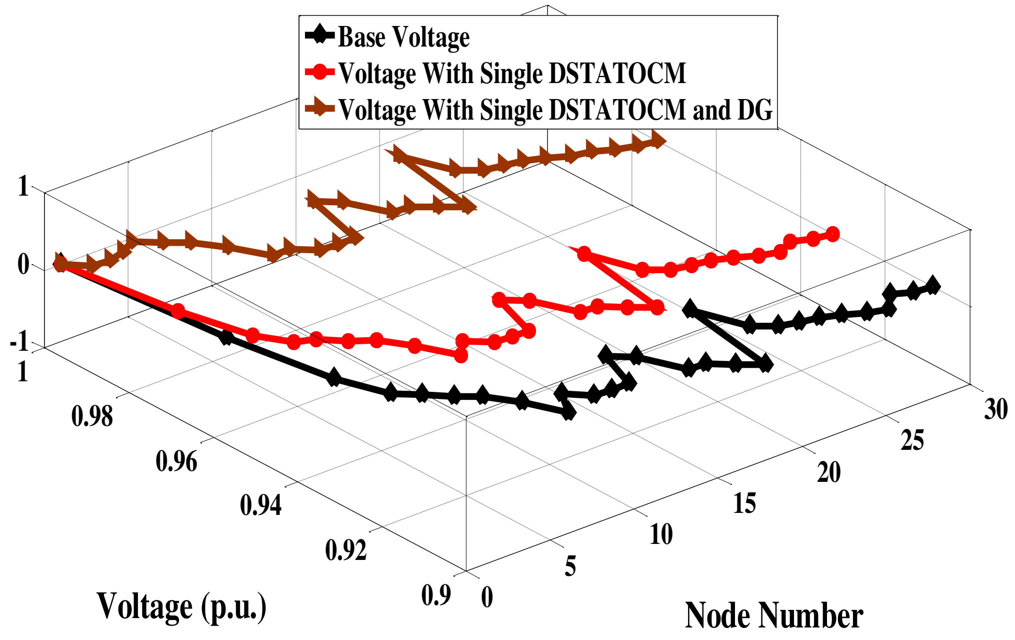

Figure.5.9: Voltage magnitude with DSTATCOM and DG at node 5

5.3.4.2.Benefit analysis of the proposed approach

Table 5.5 and 5.6 shows the benefit of proposed approach. 31.01% and 54.38 % power losses are reduced when single DSTATCOM and DG alone have been respectively allocated in RDS. When both the devices are allocated simultaneously in RDS at same location, the 80.53% of power losses are reduced respectively. Also, it is seen in Fig.5.7 the system power losses are affected significantly when the devices are allocated at the nodes 5, 10, 14 and 20.

5.4. Conclusion

This paper presents the reactive power compensation in RDS by integrating the multiple-DSTATCOM and the combination of both DSTATCOM and DG in the system. FBS load flow technique is applied for the calculation of power flow and losses in the system. The amount of phase angle injection by the DSTATCOM that must be injected into the system to compensate the reactive power to reduce the power loss is considered from the modeling of DSTATCOM provided in chapter 3. The 69-bus, and 30-bus RDS are used as a test systems to illustrate the incorporation of multiple-DSTATCOM and DSTATCOM and DG combination. DEA provided in chapter 3 is used to optimize the location and phase angle injection of DSTATCOM to compensate the required amount of reactive power in 69-bus RDS. The ESM algorithm is used to optimize the The optimal allocation of DSTATCOM and DG to compensate the required amount of reactive power in IEEE-30 bus RDS. The load flow results in MATLAB shows the impact of Multiple-DSTATCOM and DSTATCOM and DG to reduce the power loss. Installation of multiple DSTATCOMs leads maximum of 35.6% of power loss reduction in this approach. The problem formulated for the allocation of DSTATCOM and DG is integrated into the forward-Backward sweep load flow algorithm to study the impact of the allocation of these devices. The ESM algorithm is used to determine the best size and location of DSTATCOM and DG to achieve the best possible reduction in power loss. The combination of both DSTATCOM and DG allocation in IEEE 30-bus RDS minimizes the 80.53% of system active power loss, which provides great benefit to the utility customers and consumers.

Chapter 6

Conclusion and Future Scope

6.1. Conclusion

- This thesis is focused on the optimal planning of Distribution STATCOM in distribution systems to optimize the total energy loss cost and the total net profit (total economic cost benefit) per annum and planning horizon. These objectives are achieved by compensating the reactive power in DS by allocating the DSTATCOM optimally.
- The new phase angle model of DSTATCOM is devolved to determine the rating of DSTATCOM to generate reactive power. The reactive power is compensated by injecting the phase angle.
- The forward-backward sweep load flow algorithm is developed to suitably incorporate the DSTATCOM in distribution systems and to evaluate the power loss, line current and node voltages of distribution systems.
- A new objective function is formulated to evaluate the objectives of the thesis such as optimization of power loss, energy loss cost, total net profit and voltage profile.
- The PWF and PH have been considered in objective function since the planning of DSTATCOM in distribution system occurs once for planning era.
- The ESM and DEA optimizing techniques are used to find the optimal size and location(s) of DSTATCOM. The soft constraints method has been implemented in optimization technique to avoid the abnormal conditions in the operation of distribution system. Line currents, node voltages and the size of the DSTATCOM are maintained in safe limits using soft constraints technique.
- The multiple DSTATCOMs and the combination of both DSTATCOM and DG have also been allocated optimally to compensate the reactive power in the DS so that the best approach to compensate the reactive power in DS can be opted.
- To validate the proposed approach 30, 33, and 69 bus RDNs are considered as test systems. The results performance of proposed approach are compared with several

previous investigations and it is observed that the proposed approach is better and profitable to implement practically in DISCO's.

6.2. Future Scope

Research work presented in this thesis can be extended in following dimensions in future.

1) Control strategy of single and multiple DSTATCOM(s) can be investigated to control the DSTATCOM according to the requirements of the distribution systems to mitigate the power quality issues.
2) Multi objective fuzzy based Pareto optimization technique can be developed to allocate DSTATCOM in distribution systems to mitigate high power loss, harmonics, voltage stability and linelodabilty at different load conditions etc.
3) The combinatorial allocation of DSTATCOM and DVR in distribution systems can fulfill the purpose of both shunt and series compensations to mitigate power quality issues.
4) Modeling of multiple DSTATCOM

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Thesis Disseminations

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