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OPTIMAL PLACEMENT OF DISTRIBUTED GENERATION IN DISTRIBUTION NETWORKS TO REDUCE CONGESTION

1st Er. Neha Rani, 2nd Er. Jaswinder Singh

1st Assistant Professor, 2nd Assistant Professor

Department of Electrical Engineering

Punjab Institute of Technology Guru Teg Bahadur Garh, Moga, Punjab, India

Abstract: This paper proposes a particle swarm optimization (PSO) algorithm for optimal placement of distributed generation (DG) in distribution networks to minimize congestion. The PSO provides a population-based search procedure in which individuals called particles change their positions with time. During flight, each particle adjusts its position according to its own experience, and the experience of neighboring particles, making use of best position encountered by itself and its neighbors. Initially, the algorithm randomly generates the particle positions representing the size and location of DG. Each particle will move from its current position using the velocity and the distance from current best local and global solution reached. The velocity consists of inertia of the particle, memory, and cooperation between particles. The proposed PSO algorithm is used to determine optimal sizes and locations of DG and FACTS devices. Test results indicate that PSO method can obtain better results than the simple heuristic search method on the 30-bus radial distribution systems. The PSO can obtain maximum loss reductions for each of optimally placed DG and FACTS devices. Moreover, voltage profile improvements are also observed.

***Index Terms* - FACTS (Flexible AC Transmission system), STATCOM (Static Compensator), PSO (Particle Swarm Optimization), DG (Distributed Generations), UPFC (Unified Power Flow Controller).**

I. INTRODUCTION

Distributed Generation (DG) or FACTS devices are small generators spotted throughout a power system network, providing the electricity locally to load customers [1]. DG or FACTS devices can be an alternative for industrial, commercial and residential applications. DG or FACTS devices makes use of the latest modern technology which is efficient, reliable, and simple enough so that it can compete with traditional large generators in some areas [2] [3]. Placement of DG or FACTS devices is an interesting research area due to economical reason. Distributed generation systems (such as fuel cells, combustion engines, micro-turbines, etc.) can reduce the system loss and defer investment on transmission and distribution expansion. Appropriate size and optimal locations are the keys to achieve it [4] [5]. Optimal placement of DG or FACTS devices in distribution network is an optimization problem with continuous and discrete variables. Many researchers have used evolutionary methods for finding the optimal DG or FACTS placement [6]-[9]. In [10], a Newton-Raphson algorithm based load flow program is used to solve the load flow problem. The methodology for optimal placement of only one DG of FACTS is proposed. Moreover, the heuristic search requires exhaustive search for all possible locations which may not be applicable to more than one DG or FACTS devices. Therefore, in this paper, PSO method is proposed to determine the optimal location and sizes of DG or FACTS devices to minimize the total real power loss of the distribution systems. The organization of this paper is as follows. Section 2 addresses the problem formulation. The modeling of DG and FACTS devices with PSO algorithms and computational procedure for the OPDG problem is explained in Section 3. Simulation result on the test systems are illustrated in Section 4. Then, the conclusion is given in Section 5.

II. PROBLEM FORMULATION

The real power loss reduction in a distribution system is required for efficient power system operation. The loss in the system can be calculated by equation (1) [11], given the system operating condition,

$$P_L = \sum_{i=1}^{n} \sum_{j=1}^{n} A_{ij}(P_i P_j Q_i Q_{j)} + B_{ij}(Q_i P_j - P_i Q_j) \quad (1)$$

Where,

$$A_{ij} = \frac{R_{ij}\cos(\delta_i - \delta_j)}{V_i V_j}$$

$$B_{ij} = \frac{R_{ij}\sin(\delta_i - \delta_j)}{V_i V_j}$$

where, P_i and Q_i are net real and reactive power injection in bus 'i' respectively, R_{ij} is the line resistance between bus 'i' and 'j', V_i and δ_i are the voltage and angle at bus 'i' respectively. The objective of the placement technique is to minimize the total real power loss. Mathematically, the objective function can be written as:

$$\text{Minimize } P_L = \sum_{k=1}^{N_{SC}} Loss_k \quad (2)$$

Subject to the power balance constraints

$$\sum_{i=1}^{N} P_{DGi} = \sum_{i=1}^{N} P_{Di} + P_L \quad (3)$$

$$V_i^{min} \leq V_i \leq V_i^{max} \quad (4)$$

where: $Loss_K$ is distribution loss at section k, N_{SC} is total number of sections, P_L is the real power loss in the system, P_{DGi} is the real power generation DG at bus i, P_{Di} is the power demand at bus i.

III. MODELING OF DG AND FACTS DEVICES

1. Modeling of STATCOM

A STATCOM (static synchronous compensator), also known as a static synchronous condenser (STATCON), is a regulating device used on alternating current electricity transmission networks. It is based on a power electronics voltage-source converter and can act as either a source or sink of reactive AC power to an electricity network. If connected to a source of power it can also provide active AC power. It is a member of the FACTS family of devices. It is inherently modular and electable. These compensators are also usable to reduce voltage fluctuations. A STATCOM is a voltage source converter (VSC)-based device, with the voltage source behind a reactor. The voltage source is created from a DC capacitor and therefore a STATCOM has very little active power capability. However, its active power capability can be increased if a suitable energy storage device is connected across the DC capacitor. The reactive power at the terminals of the STATCOM depends on the amplitude of the voltage source. For example, if the terminal voltage of the VSC is higher than the AC voltage at the point of connection, the STATCOM generates reactive current; conversely, when the amplitude of the voltage source is lower than the AC voltage, it absorbs reactive power.[5] The response time of a STATCOM is shorter than that of a static VAR compensator (SVC)[6], mainly due to the fast switching times provided by the IGBTs of the voltage source converter. The STATCOM also provides better reactive power support at low AC voltages than an SVC, since the reactive power from a STATCOM decreases linearly with the AC voltage (as the current can be maintained at the rated value even down to low AC voltage).

The mathematical modeling of STATCOM is also explained below-

A typical A. C. System is used in this thesis to show performance of STATCOM. The basic configuration of STATCOM is shown in Fig. 3.8 STATCOM consist of resistance, leakage inductance, and VSI and DC capacitor. Resistance and inductance acts as magnetic coupling to the system. They provide isolation to inverter circuit and grid circuit. DC capacitor provides constant voltage, it acts as source. IGBT with anti-parallel diode is used. IGBT performs converter action whereas Diode performs rectification action. Following equations are used to calculate resistance, leakage inductance and DC side capacitance First order differential equation for the ac-side circuit of the STATCOM is:

$$\frac{dI_{sa}}{dt} = {}^{1}/_{L_s}\,(-R_s * I_{sa} + E_{sa} - E_{ta}) \qquad (5)$$

$$\frac{dI_{sb}}{dt} = {}^{1}/_{L_s}\,(-R_s * I_{sa} + E_{sb} - E_{tb}) \qquad (6)$$

$$\frac{dI_{sc}}{dt} = {}^{1}/_{L_s}\,(-R_s * I_{sc} + E_{sc} - E_{tc}) \qquad (7)$$

These equations are converted on R-I frame of references (the synchronously rotating frame of references) as follows:

$$\begin{bmatrix} I_{sR} \\ I_{sL} \end{bmatrix} = \begin{bmatrix} \frac{-R_s}{L_s} & w0 \\ -w0 & \frac{-R_s}{L_s} \end{bmatrix} \begin{bmatrix} I_{sR} \\ I_{sL} \end{bmatrix} + \frac{1}{L_s} \begin{bmatrix} E_{sR} & E_{tR} \\ E_{sl} & E_{tl} \end{bmatrix} \qquad (8)$$

The DC side equation of STACOM is

$$\frac{dV_{dc}}{dt} = {}^{1}/_{C_s}\,(I_{dc} + V_{dc}) \qquad (9)$$

Instantaneous powers at the ac and dc terminals of the converter are equal, giving the following power balance equation:

$$V_{dc} * I_{dc} = {}^{3}/_{2}\,(E_{sR} * I_{sR} + E_{sl} * I_{sl}) \qquad (10)$$

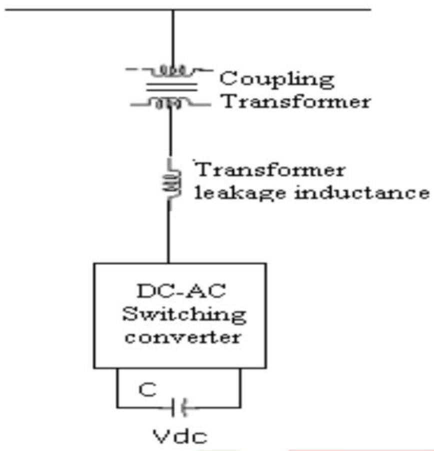

Fig 1 Single line diagram of STATCOM

2. Modeling of DG

Certain type of DGs like photovoltaic will produce real power only. To find the optimal DG size at but 'i', when it supplies only real power, the necessary condition for minimum loss is

$$P_i = P_{DGi} - P_{Di} = -\frac{1}{A_{ii}} \sum_{\substack{j=1 \\ j \neq i}}^{n} (A_{ij}P_j - B_{ij}Q_j) \qquad (11)$$

From equation (6), we obtain the following relationship:

$$P_{DGi} = P_{Di} - \frac{1}{A_{ii}} \sum_{\substack{j=1 \\ j \neq i}}^{n} (A_{ij}P_j - B_{ij}Q_j) \qquad (12)$$

Equation (7) gives the optimal DG size for each bus so as to minimize the total real power loss.

3. Unified Power Flow Controller (UPFC)

The UPFC is second generation controller. The two voltage source converter is consisting in UPFC, which inject power into the lines. Basically the UPFC is combination of STATCOM and SSSC controller because in Unified Power Flow Controller, one converter act as a shunt connected device and another converter act as a series connected device. The shunt connected voltage source converter work as a Static Synchronous Compensator and another series voltage source converter act as SSSC. In figure1.2, we can see that the capacitor is connected between the two voltage sources converters are used for the transient unbalance power.

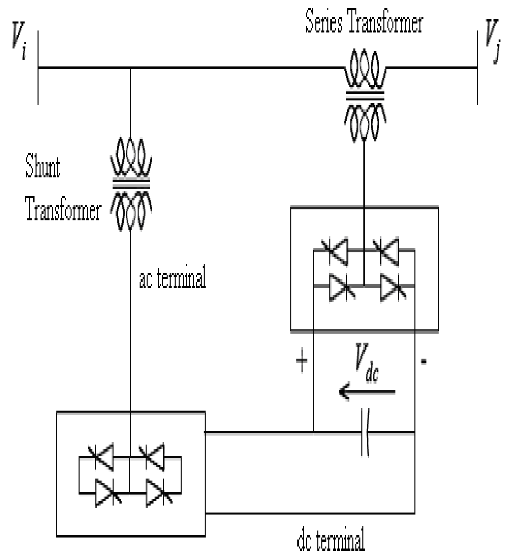

Figure 2: Configuration of UPFC

The UPFC is made from the two converters with semi conductor devices having turn-off capability. The active power demand of semi conductor in main DC link point from the link is provided by the shunt converter of UPFC. The series converter of the Unified Power Flow Controller is for regulate voltage at the fundamental frequency with the controllable magnitude and phase angle. This is given to line through the coupling transformer. The converter output voltage is injected directly into line for direct voltage control. The reactive power is generated and absorbed by converters internally and transfers the active power to its DC terminal. In the DC link, the reactive power of each converter is not flowing. Basically the dc link provides path to exchange the active power between the converters. The series voltage of line is injected by the series converter. By controlling the angle and magnitude of the injected voltage, the power flow throw the line is regulated. The converter which is in the Unified Power Flow Controller has capability to electromechanically generate or absorb the power. Both the converter exchanges the reactive power with AC system independently. The power is injected and supplied by dc link. But when losses in the Unified Power Flow Controller and transformer are neglected, in this time the power exchange is zero between the UPFC and AC system. When the line to ground fault occurs in system, the power in the lines is reduced and losses in the system is increase. In meantime, Unified Power Flow Controller injects the voltage into the line and support the voltage. The system become stable and manages the active power flow in the line, because UPFC consist a two voltage source converter which generate and absorb the reactive power according to requirement of system.

IV. Power Quality issues and techniques in the power system

The power quality issue is occurring in power system due to the non standard voltage and current. By maintaining the voltage magnitude constant, we can increase the power quality of system. There are some methods in which reactive power can be controlled within limits. For this purposes, many researcher use the D-STATCOM controller because the aim of electrical utility is to provide the voltage at constant magnitude. The non-linear load generates the harmonics. Due to the harmonic current, the voltage and current gets distorted which affect the system performance. The efficiency of generation and distribution system gets reduced. The life of electrical equipment is also reduced. D-STATCOM FACTs controller is used to support the electrical network. Basically the D-STATCOM is voltage source converter based device which can work as a reactive power source. Some time by using the D-STATCOM power factor is improved and harmonics are reduced.

FACTs controllers are basically divided into two types. First is converter based and second is non converter based. Non converter based is static VAR compensator and Thyristor-Controlled Series Capacitor (TCSC). These devices are used because they generate or absorb the reactive power without using the capacitor and reactor. Converter based controller consist of STATCOM, SSSC, UPFC and IPFC. These controllers have capability to individually control the active and reactive power. From these controllers series connected devices are static synchronous series converter (SSSC) and interline power flow controller (IPFC). These controllers are capable for operating in inductive and capacitive mode. IPFC consist of number of DC to AC inverters. These inverters provide the reactive power compensation to different lines. Due to the devolvement of power generation and transmission system, the stability is a major issue in power system. This paper described FACTs devices for explore of some new possibilities for power flow control. There are some challenges like phase angle control, voltage control and impedance control which are encountered by the industry related with FACTs controllers. The list of first generation controllers are given below:

- Static VAR compensator(SVC)
- Thyristor-controlled phase shifter(TCPS)
- Thyristor controlled series capacitor(TCSC)

The second generation controllers are given as:

- Static synchronous series compensator
- Unified Power Flow Controller
- Interline power flow controller

Study of different FACTs controllers, which are normally used for power flow management and for stability of system were also described in [43]. The FACTs technology is based on power electronic converters, offers an opportunity to increase the controllability, stability and power transfer capacity of the line. The limitation of transmission system to transfer the transient power, are given below.

- Angular stability
- Magnitude of voltage
- Thermal limits
- Transient stability
- Dynamic stability

The objective of various controllers was described. The FACTs controllers were used to maintain the voltage within acceptable limit. The main objective of FACTs controllers are given as:

- Loading of transmission line near to their thermal limits.
- The regulation of power flow in transmission routes.
- The emergency control for Prevention of cascading outage.

The controllers were mainly used for controlling real and reactive power of the system [44]. The complexity of electrical power system has been increased from many years, because of existing transformer load near to their closer limit. Analysis had been done based on changing nature of power system.

V. Particle Swarm Optimization Algorithm

Particle swarm optimization (PSO) is a population-based optimization method first proposed by Kennedy and Eberhart in 1995, inspired by social behavior of bird flocking or fish schooling [16]. The PSO as an optimization tool provides a population-based search procedure in which individuals called particles change their position (state) with time. In a PSO system, particles fly around in a multidimensional search space. During flight, each particle adjusts its position according to its own experience (This value is called P best), and according to the experience of a neighboring particle (This value is called G best), made use of the best position encountered by itself and its neighbor (Figure 1).

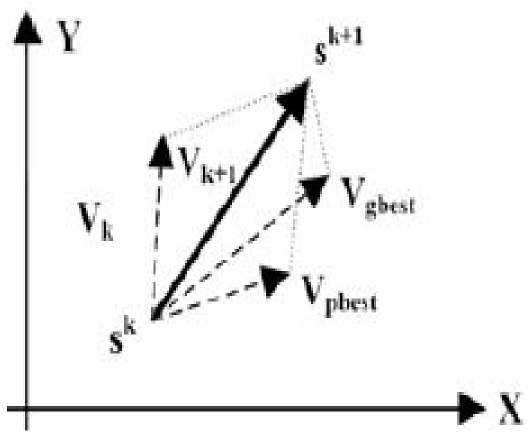

Fig 3 Concept of searching point by PSO

This modification can be represented by the concept of velocity. Velocity of each agent can be modified by the following equation:

$$V_{ik+1} = w.V_{ik} + C_1.rand1.(P_{besti} - S_{ik}) + C_2.rand2.(G_{best} - S_{ik}) \quad (13)$$

Using the above equation, a certain velocity, which gradually gets close to p best and g best, can be calculated.

The current position (searching point in the solution space) can be modified by the following equation:

$$S_{ik+1} = S_k + V_k + 1 \quad (14)$$

Where $S_k$is current searching point, S_k+1 is modified searching point, $V_k$is current velocity, V_k+1 is modified velocity of agent i, p best v is velocity based on p best, g best v is velocity based on g best, n is number of particles in a group, m is number of members in a particle, p best is p best of agent i, g best is g best of the group, $w_i$is weight function for velocity of agent i, $C_i$is weight coefficients for each term.

The following weight function is used:

$$w_i = w_{max} - \frac{w_{max} - w_{min}}{K_{max}}.k \quad (15)$$

Where w_{max} *and* $w_{min}$are the minimum and maximum weights respectively .k and kmax are the current and maximum iteration. Appropriate value ranges for C1 and C2 are 1 to 2, but 2 is the most appropriate in many cases. Appropriate values for w_{max} *and* $w_{min}$are 0.4 and 0.9 [17] respectively.

Particle Swarm Optimization Procedure

The PSO-based approach for solving the OPDG problem to minimize the loss takes the following steps:

Step 1: Input line and bus data, and bus voltage limits.

Step 2: Calculate the loss using distribution load flow based on backward-forward sweep.

Step 3: Randomly generates an initial population (array) of particles with random positions and velocities on dimensions in the solution space. Set the iteration counter k = 0.

Step 4: For each particle if the bus voltage is within the limits, calculate the total loss in equation (1). Otherwise, that particle is infeasible.

Step 5: For each particle, compare its objective value with the individual best. If the objective value is lower than P best, set this value as the current P best, and record the corresponding particle position.

Step 6: Choose the particle associated with the minimum individual best P best of all particles, and set the value of this P best as the current overall best G best.

Step 7: Update the velocity and position of particle using (12) and (13) respectively.

Step 8: If the iteration number reaches the maximum limit, go to Step 9. Otherwise, set iteration index k = k + 1, and go back to Step 4.

Step 9: Print out the optimal solution to the target problem. The best position includes the optimal locations and size of DG or FACTS device, and the corresponding fitness value representing the minimum total real power loss.

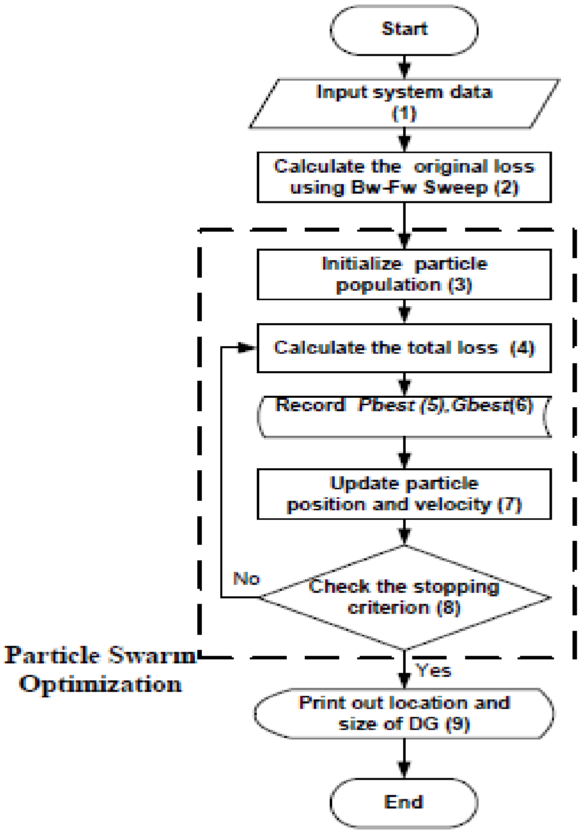

Fig 4 PSO-OPDG computational procedure

VI. COMPUTATIONAL RESULTS

30 Bus systems is used for the analysis.

CASE 1: WITHOUT USING STATCOM

In this case, the analysis is done on 30-Bus system and the various parameters are calculated by using the Particle Swarm Optimization. The value of the calculated parameters and graphs are compared with the flower pollination algorithm and are shown below-

Voltages at each bus in per unit

Bus Number	Voltage at Each Bus (PSO)	Voltage at Each Bus (FPA)
1	0.9656	0.9824
2	0.9630	0.9787
3	0.9646	0.9769
4	0.9652	0.9764
5	0.9579	0.9713
6	0.9613	0.9723
7	0.9502	0.9623
8	0.9501	0.9611
9	0.9845	0.9903
10	0.9968	0.9998
11	0.9845	0.9903

12	1.0213	1.0174
13	1.0792	1.0645
14	1.0103	1.0066
15	1.0124	1.0092
16	1.0038	1.0028
17	0.9937	0.9955
18	0.9943	0.9933
19	0.9871	0.9873
20	0.9886	0.9896
21	1.0066	1.0093
22	1.0135	1.0160
23	1.0293	1.0256
24	1.0166	1.0167
25	1.0438	1.0438
26	1.0267	1.0267
27	1.0690	1.0690
28	0.9719	0.9820
29	1.0500	1.0500
30	1.0391	1.0391

Total real power loss in KW (PSO)

3158.17

Total reactive power loss in KVAR (PSO)

16376.14

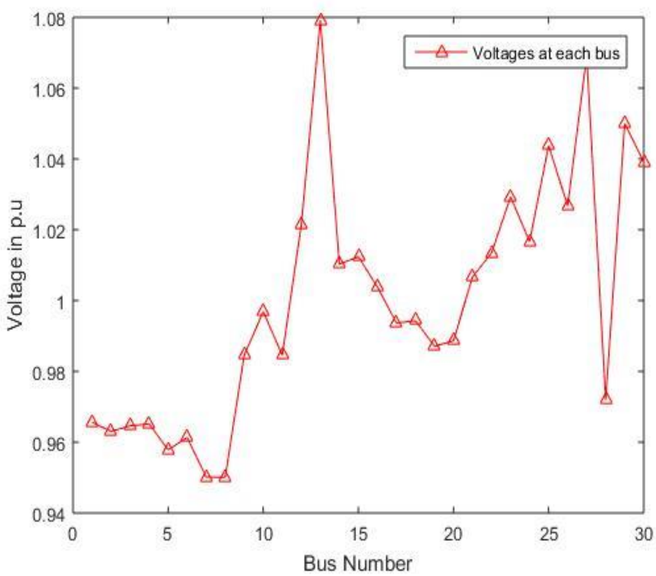

Fig 5 Voltages at each Bus

Total Congestion Cost in ($/KVA) (PSO)

115398.76

Maximum congestion cost is ($/KVA) (PSO)

71994.70

Most congested line is 6 to 8

CASE 2: USING STATCOM

In this case, the location of FACT device to be placed is calculated using the Congestion Cost formula as given below-

Congestion cost = abs (pf(j)*(LMP(2) – LMP(1))) (15)

Now, after calculating the location of the FACT devise using the above formula, the value of the FACT device to be placed on that location is calculated using the Particle swarm Optimization. The results and the graph of the various parameters obtained are shown below-

Voltages at each bus in p.u

Bus Number	Voltage at Each Bus (PSO)
1	0.9656
2	0.9630
3	0.9646
4	0.9652
5	0.9579
6	0.9613
7	0.9502
8	0.9501
9	0.9845
10	0.9968
11	0.9845
12	1.0213
13	1.0792
14	1.0103
15	1.0124
16	1.0038
17	0.9937
18	0.9943
19	0.9871
20	0.9886
21	1.0066
22	1.0135
23	1.0293
24	1.0166
25	1.0438

26	1.0267
27	1.0690
28	0.9719
29	1.0500
30	1.0391

Best value of STATCOM

32.65

Total Congestion Cost in ($/KVA)

81589.93

Maximum congestion cost is ($/KVA)

52720.88

Most congested line is 6 to 8

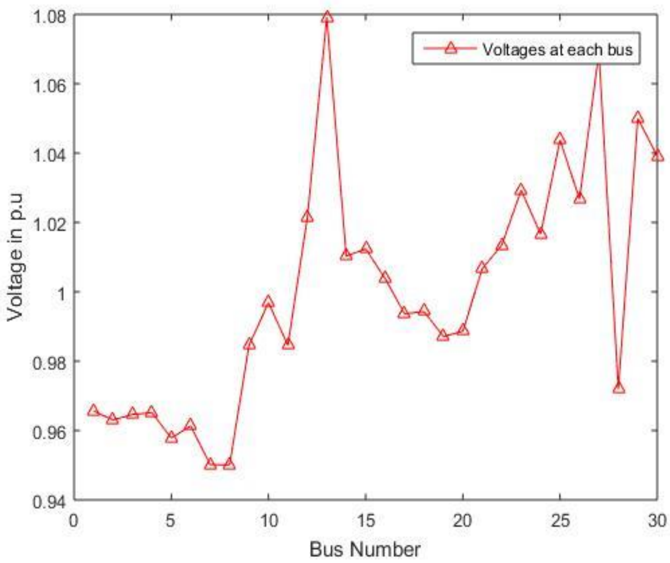

Fig 6 Voltages at each Bus using STATCOM

VII. CONCLUSION

The electrical power demand has increased rapidly in the recent years. However, the expansion of electrical power transmission facilities is limited due to number of economic and social constraints. Electric utilities are forced to operate the system close to their thermal and stability limits. Also, a stressed power system, either due to increased loading or due to severe contingencies, often leads to situation where system no longer remains in the secure operating region. Hence, the utilities are left with the option to increase the utilization rates of the existing transmission lines using some modern elements in the system. FACTS devices or DG's are such elements which help to reduce the power flows in heavily loaded lines, resulting in an increased load-ability, low system loss, improved stability, and security margin of the network. However, the effectiveness and efficiency of the FACTS devices or DG''s depend on the locations at which they are placed, and their settings. This work mainly focused on the enhancement of power system by mainly reducing the congestion cost by suitably placing the optimal FACTS devices or DG's on the selected location and thereby reducing the congestion cost and the various parameters are also controlled such as voltage, real and reactive power loss.

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