OPTIMAL SITING AND SIZING OF D-STATCOM USING PARTICLE SWARM OPTIMIZATION

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Abstract - *The electrical power system consists of generation, transmission, distribution system. The transmission system links the generators to substations, which supply power to the user through the distribution system. The Distribution system is most associated with power loss and has least reliability due to various reasons such as low voltage levels and multiplicity of faults. This work is applying particle swarm optimization algorithm (PSO) that aims to achieve the power loss reduction and maximum voltage profile in radial distribution network with Distribution Static Compensator (D-STATCOM). D-STATCOM is used to improve bus voltage profile. Voltage stability index is used to identify place for placing D-STATCOM. An effectively particle swarm optimization is used to search the best location and is employed to deduce the size and location of D-STATCOM for the weak buses. The validity of the method is tested in the IEEE12,IEEE34 Bus radial distribution system and Checkanurani substation rating of 110/11 KV in Madurai. Load flow analysis is performed and the bus voltage and power loss is obtained in MATLAB. The results obtained are compared without and with D-STATCOM. By the optimal placement and sizing of D-STATCOM the voltage profile improved and the power loss reductions are obtained in the Checkanurani substation located in Madurai, Tamilnadu.*

Key Words: D-STATCOM, Load flow analysis, IEEE12, IEEE34 Bus radial distribution system, Checkanurani Substation, Optimum location, Optimum size

1. INTRODUCTION

The power system is a network that consists of generation, transmission and distribution system. The power plants, transformers, transmission lines, substations, distribution lines, and distribution transformers are the six main components of the power system. The generator generates the power which is step-up or step- down through the transformer for transmission. The transmission system carries the overhead lines which transfer the generated electrical energy from generation to the distribution substations. Distribution systems connect all the consumers in an area to the bulk power sources.

Distribution systems have high R/X ratio which results in high power loss which leads to voltage instability. Series voltage regulator and shunt capacitors are the two conventional ways of maintaining the voltages of the distribution system at an acceptable range. But, these devices have some disadvantages that are conventional series voltage regulators cannot generate reactive power and have quite slow response because of their step by step operations. The disadvantage with the shunt capacitors is that they cannot generate continuously variable reactive power.

Test system considered is IEEE12, IEEE34 Bus and Checkanurani substation in Madurai. Checkanurani substation is a step down substation with a rating of 110/11 KV. It consists of six outgoing feeders. Namely, Karumathur, Thenpalanji, Gandhinagar, Kannanur, Powergrid, and University. Some distribution transformers are overloaded, this has resulted in more losses and under voltage in the system. To overcome this issue, the loads were disconnected from the overloaded transformers and reconnected to the connected to the nearby lightly loaded transformers and then the load flow program is executed to find the feeder losses by using sweep algorithms. The shunt capacitors are also placed to improve bus voltage and the results did not turn up to the expected level.

To overcome these problems FACTS devices are used. In this work, Distribution STATCOM (D-STATCOM) is proposed. D- STATCOM is a shunt connected voltage source converter. It is used to compensate for power quality problems such as voltage sag, voltage fluctuation, voltage unbalance and unbalanced load. The Voltage stability index method is used to find the optimal location and sizing D-STATCOM. A Particle swarm optimization algorithm is used to find the optimal location and sizing of DSTATCOM. D- STATCOM is modeled for the determination of its size by assuming different reference voltage. Forward and backward Sweep algorithm is used to carry out the load flow analysis of Standard IEEE 12 Bus and IEEE 34 Bus Radial distribution system and Checkanurani substation. The D-STATCOM is used to improve the voltage profile and minimize the transmission loss.

2. PROBLEM DESCRIPTION AND FORMULATION

2.1 IDENTIFICATION

The reduction of losses and maintaining a voltage profile of the Distribution feeders in a radial distribution system. This can be done by using D-STATCOM of optimal rating at appropriate locations and sizing of D-STATCOM

2.2 OBJECTIVE

- To find the optimal location of D-STATCOM using voltage stability index.
- To determine the sizing of D-STATCOM using particle swarm optimization algorithm.
- To improve voltage profile and reduce power loss in the distribution system by using D-STATCOM.

2.3 PROBLEM FORMULATION

The objective of the optimal placement and sizing of D- STATCOM is to minimize the total power loss in the distribution network with voltage profile improvement.

$$\text{Min } f = \min (PT\ Loss)$$

CONSTRAINTS:

The reactive power injected by D-STATCOM to the system is limited by upper and lower bounds given

$$Q_{min} \leq Q_{D\text{-}STATCOM} \leq Q_{max}$$

The system voltage in all buses should be an acceptable range $V_{min} \leq V_i \leq V_{max}$

V_i is the voltage of ith bus and i bus varies from 1 to number of buses.

2.4 LOAD FLOW ANALYSIS

2.4.1 Calculation of load current

The load current at any bus is given as:

$$IL_n = (P_n - jQ_n) / V_n \quad \text{Where } n=1,2 \ldots N \quad \ldots (1)$$

Where,

IL= Load Current

N= total. No. of buses

Pn= Active power

Qn= Reactive power

Vn= Bus Voltage

2.4.2 Backward Sweep

Backward Sweep algorithm is used to calculate the branch current starting from the last layer towards the branches connected to root node.

The relation between load current and branch current can be found by using KCL equation

The matrix can Written as:

$$[IB] = [BIBC]\,[IL] \quad \ldots (2)$$

Where,

IB= Branch Current

BIBC= Bus injection to Branch Current Matrix

2.4.3 *Forward Sweep*

Forward sweep algorithm is used to calculate the voltage at each bus starting from branches from first layer to last layer.

$$V_n(K) = V_m(K) - I_B(K) * Z_m(K) \quad \ldots (3)$$

Where,

K=1,2,.....Nb

Nb= total no. of. Branches= N-1

Vn(K)= receiving end Voltage

Vm(K)= sending end Voltage

2.4.4 Power losses:

Power loss= Bus voltage* Branch Current ....(4)

3. OPTIMAL PLACEMENT OF D-STATCOM

Voltage Stability Index method is used to find the optimal location of D-STATCOM in the buses. The bus with highest value of stability index is selected as candidate bus.

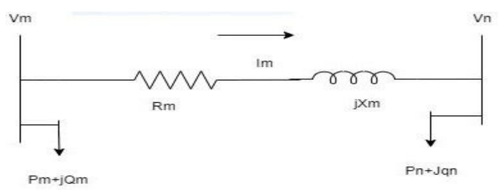

Fig 1: Single line diagram of two bus distribution system

The expression for stability index is

$$S.I = 4 * R_m * (P_n^2 + Q_n^2) / (V_m^2 * P_n) \quad \ldots (5)$$

Where,

I m = Branch current
R m= Branch resistance
X m= Branch reactance
R = Resistance (p.u.)
P = Real Power (p.u.)
Q = Reactive power (p.u.)
V m= Voltage (p.u.)

4. MATHAMATICAL MODELLING OF D-STATCOM

D-STATCOM is a shunt connected voltage source device. It has three components such as voltage source converter (VSC), coupling reactor and controller. The D-STATCOM is modelled by calculating injected current and injected reactive power with different reference voltage.

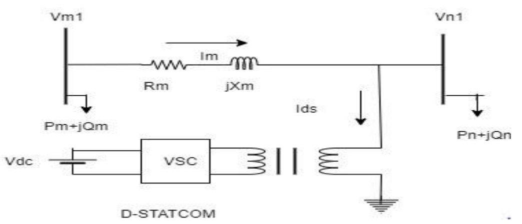

Fig 2: Single line diagram of two bus distribution system with D-STATCOM

$Im = (Pn - jQn) / Vn^*$ .... (8)

$IDS = (Vn1\cos\theta n - h1)/(-h4\sin\theta n - h3\cos\theta n)$ .... (9)

$h1 = real(Vm1\angle\theta m) - real(Zm.Im\angle\delta)$

$h3 = -Xm$

$h4 = -Rm$

$QDS = (Vm1\angle\theta n).(IDS\angle(\pi/2+\theta n))$ .... (10)

* denotes the complex conjugate.

Where,

QDS= Reactive power by D-STATCOM
IDS = Current injected by D-STATCOM
Vm1= Sending end voltage (previous bus)
Vn1= Receiving end voltage (candidate Bus)
θm=phase angle of Vm1
θn=phase angle of Vn1
δ= phase angle of Im

5. PROPOSED METHODOLOGY

Algorithm for radial distribution system is given below:

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

Step 2: Calculate the power loss using backward-forward sweep in distribution system.

Step 3: Randomly produces an initial population of particles with random positions and velocities on volume in the solution space.

Step 4: For each and every particle if the bus voltage is within the limits in each particle, calculate transmission loss or, that particle is infeasible.

Step 5: For each particles, analyze 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 note the corresponding particle position.

Step 6: Update the velocity and position of particle respectively.

Step 7: If the iteration number attain the maximum limit, go to Step8 Or set iteration i = i+ 1, and go back to Step 4.

Step 8: Print the optimal solution to the target problem. The best position includes the optimal locations and size of D-STATCOM, and the corresponding fitness value representing the minimum power loss.

6. TEST SYSTEM

The test system considered in this paper is a step-down substation with the rating of 110/11kV. The substation has two common buses and six outgoing feeders. Bus1 is connected to station transformer and Bus2 is connected to potential transformer. These buses are interconnected through common switch. Each bus consists of three feeders i.e., Bus1is connected to Power grid, Thenpalanji and Kannanur. Bus2 is connected to University, Gandhi Nagar and Karumathur. The feeders are interconnected through common switch. Totally the test system consists of six feeders.

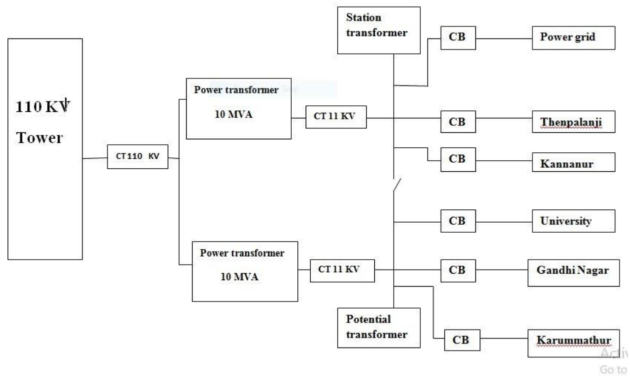

Fig 3: Single line diagram of Checkanurani Substation

Karumathur, Gandhinagar, Kannanur and Thenpalanji feeders consist of twenty, twenty two, forty and seventeen distribution transformers with the total rating of 2479 KVA, 2763 KVA,5877 KVA, and 2075 KVA respectively. The power grid and university feeders consist of one and three distribution transformers with the rating of 250 KVA and 100 KVA. The total load for the test system is 22202.15 KW. The total capacities of the distribution transformers are 13444 KVA.

7. PARTICLE SWARM OPTIMIZATION

Particle swarm optimization is a computational method that optimizes a problem by iteratively trying to improve a candidate solution with regard a given measure of quality.

Update velocity:

$$V_i^{k+1}=c*[wv_i^k+c_1r1*(P_{best}-S_i^k)+c_2r2*(G_{best}-S_i^k)]$$

Update position:

$$S_i^{k+1}=S_i^k+V_i^{k+1}$$

Where,

w= weighting coefficient

c_1, c_2= acceleration coefficient

r1, r2= random numbers between 0 and 1 which can change the speed and accuracy of algorithm.

P_{best}= best position that has been found by i th iteration to k th iteration

G_{best}= best position of all particles.

8. RESULTS AND DISCUSSION

The test results are analyzed for IEEE12, IEEE34 bus radial distribution system. Checkanurani substation results are analyzed for 4 feeders only, namely Karumathur, Thenpalanji, Gandhi Nagar and Kannanur feeders. For other two feeders the voltage profile is found to be within limit and hence the placing of D-STATCOM is not recommended. The results are presented below:

8.1 IEEE12 BUS RADIAL DISTRIBUTION SYSTEM

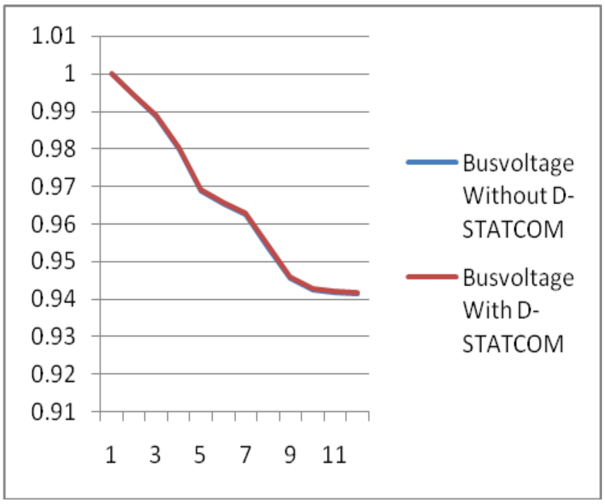

Fig 4: *Bus voltage profile in IEEE12 bus*

8.1.1 Voltage stability Index

Bus number 7 is the more stable and highest value of stability Index which is selected as candidate Bus to place the D- STATCOM in the IEEE 12 Bus radial distribution system.

Table-1 *:Optimal location of D-STATCOM at different location*

Bus number	SI for base case	SI for 10% load	SI for 20% load	SI for 30% load
2	0.0047	0.0047	0.0047	0.0047
3	0.0043	0.0043	0.0043	0.0043
4	0.0116	0.0116	0.0116	0.0116
5	0.0022	0.0022	0.0022	0.0022
6	0.0010	0.0010	0.0010	0.0010
7	0.0160	0.0160	0.0160	0.0160
8	0.0150	0.0150	0.0150	0.0150
9	0.0076	0.0076	0.0076	0.0076
10	0.0032	0.0032	0.0032	0.0032
11	0.0026	0.0026	0.0026	0.0026
12	0.0015	0.0015	0.0015	0.0015

The top three voltage stability index values are sorted in descending order and then trial and error method and particle swarm optimization will be carried out to find the optimal location among these three busses.

Table- 2 : Optimal sizing of D-STATCOM for analytical method and PSO method in base case

No of Run	Global Best position		
	Position 1	Position 2	Position 3
1	7th bus	8th bus	4th bus
2	7th bus	8th bus	4th bus
3	7th bus	8th bus	4th bus
4	8th bus	7th bus	4th bus
5	7th bus	8th bus	4th bus
6	8th bus	4th bus	7th bus
7	7th bus	8th bus	4th bus
Mode	7th bus	8th bus	4th bus

Before place the D-STATCOM the total power loss is 19.7KW. An after placing the D-STATCOM the total power loss is reduced to 12.5Kw. Two D-STATCOM placement is enough for attain the minimum loss. In before D-STATCOM, all the bus voltages are within the limit in 12 bus radial distribution system.

Table- 3: Optimal location and Sizing of D-STATCOM

Optimal Location	Sizing of D-STATCOM (KVAR)		Transmission loss (KW)	
	Analytical Method	PSO Method	Analytical Method	PSO method
7th Bus	-92.5143	-92.3716	14.6	14.6
8th Bus	-70.8147	-71.2604	14.7	14.7
4th Bus	-87.1836	- 87.4843	16.9	16.9
7th and 8th Bus	-92.5143 & -70.8147	-92.3716 & -71.2604	12.4	12.4
7th ,8th and	-92.5143	-92.3716	12.4	12.4

4th Bus	-70.8147 -87.1836	-71.2604 -87.4843		

Table-4 :*Comparison result with and without D-STATCOM*

Description	Without D-STATCOM	With D-STATCOM
Total Active power in Base case,+10% load, +20%load, +30% load (KW)	435, 436.1, 437.2, 438.3	435, 436.1, 437.2, 438.3
Total Reactive power in Base case, +10% load, +20%load, +30% load (KVAR)	390, 391.1, 392.2, 393.3	390, 391.1, 392.2, 393.3
Minimum voltage (p.u)	0.9414	0.94 19
Transmission loss in base case (KW)	19.7	12.4
Transmission loss by increasing 10% load (KW)	19.9	12.4
Transmission loss by increasing 20% load (KW)	20	12.5
Transmission loss by increasing 30% load (KW)	20.1	12.6

8.1.2 IEEE34 BUS RADIAL DISTRIBUTION SYSTEM

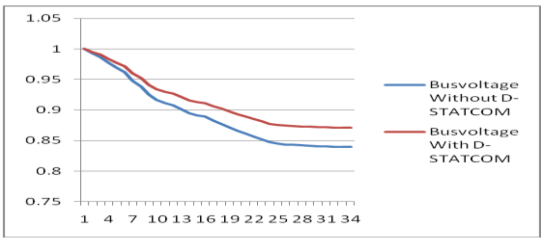

Fig 7: Bus voltage profile in IEEE34 bus

8.1.3 Voltage Stability Index:

Bus number 8 is the more stable and highest value of stability Index which is selected as candidate Bus to place the D-STATCOM in the IEEE 34 Bus radial distribution system.

Table-5: Voltage stability Index

Number	SI for base case	SI for 10% load	SI for 20% load	SI for 30% load
2	0	0	0	0
3	0.0006	0.0023	0.0023	0.0023
4	0	0	0	0
5	0.0008	0.0032	0.0032	0.0032
6	0.0008	0.0032	0.0032	0.0032
7	0	0	0	0
8	0.0017	0.0066	0.0066	0.0066
9	0	0	0	0
10	0.0011	0.0044	0.0044	0.0044
11	0	0	0	0
12	0.0005	0.0022	0.0022	0.0022
13	0.0005	0.0020	0.0020	0.0020
14	0.0003	0.0014	0.0014	0.0014
15	0.0002	0.0007	0.0007	0.0007
16	0	0.0003	0.0003	0.0003
17	0.0009	0.0002	0.0002	0.0002
18	0.0009	0.0035	0.0035	0.0035
19	0.0011	0.0044	0.0044	0.0044
20	0.0011	0.0040	0.0040	0.0040
21	0.0014	0.0055	0.0055	0.0055
22	0.0014	0.0055	0.0055	0.0055
23	0.0017	0.0066	0.0066	0.0066
24	0.0010	0.0040	0.0040	0.0040
25	0.0011	0.0044	0.0044	0.0044
26	0.0007	0.0028	0.0028	0.0028
27	0.0003	0.0022	0.0022	0.0022
28	0.0003	0.0020	0.0020	0.0020
29	0.0003	0.0011	0.0011	0.0011
30	0.0003	0.0011	0.0011	0.0011
31	0.0002	0.0011	0.0011	0.0011
32	0.0003	0.0011	0.0011	0.0011
33	0.0002	0.0008	0.0008	0.0008
34	0.0001	0.0005	0.0005	0.0005

Table-6: Optimal location of D-STATCOM at different location

S.no	No of run Global Best position		
	Position 1	**Position 2**	**Position 3**
1	8th Bus	23rd Bus	21rd Bus
2	8th Bus	23rd Bus	21rd Bus
3	8th Bus	23rd Bus	21rd Bus
4	23rd Bus	8th Bus	21rd Bus
5	8th Bus	23rd Bus	21rd Bus
6	8th Bus	23rd Bus	21rd Bus
7	23rd Bus	8th Bus	22nd Bus

8	8th Bus	23rd Bus	21rd Bus
9	8th Bus	21rd Bus	23rd Bus
10	8th Bus	23rd Bus	21rd Bus
Mode	8th Bus	23rd Bus	21rd Bus

8.1.4 Optimal sizing of D-STATCOM for analytical method and PSO method in base case

Three D-STACOM placement is enough to attain the minimum loss. The bus number 8, 23, 21 has highest values of stability Index. The losses are reduced from 131.6234 to 93.8646 KW. The minimum bus voltage increased from 0.8395 to 0.8713 pu.

Table-7: Optimal sizing of D-STATCOM for analytical method and PSO method in base case

Optimal location	Sizing of D-STATCOM (Kvar)		Transmission loss(KW)	
	Analytical method	PSO method	Analytical method	PSO method
8th bus	-398.5237	- 448.1481	125.8953	118.3140
8th and 23rd Bus	-398.5237 & 326.1786	- 448.1481 & - 448.1481	112.3405	103.2646
8th 23rd 21rdbus	-398.5237 & 326.1786 & -386.8826	- 448.1481 & - 448.1481 & - 537.7778	102.7214	93.8646

Table – 8: Comparison result with and without D-STATCOM

Description	Without D-STATCOM	With D-STATCOM
Total Active power in Base case,+10% load,+20%load, +30% load (KW)	4636.5,4639.8,4643.1, 4646.4	4636.5,4639.8,4643.1, 4646.4
Total Reactive power in Base case, +10% load, +20%load, +30% load (KVAR)	2873.5, 2876.8,2880, 2883.4	2873.5, 2876.8, 2880 2883.4
Minimum voltage (p.u)	0.8395	0.8713
Transmission loss in base case (KW)	131.6234	93.8646
Transmission loss by increasing 10% load (KW)	131.8778	94.0341
Transmission loss by increasing 20% load (KW)	132.1326	94.2037
Transmission loss by increasing 30% load (KW)	132.3399	94.3469

8.2 Checkanurani Substation

Checkanurani substation results are analyzed for 4 feeders only, namely Karumathur, Thenpalanji, Gandhi Nagar and Kannanur feeders. For other two feeders the voltage profile is found to be within limit and hence the placing of D-STATCOM is not recommended

8.2.1 Karumathur Feeder

The Bus number 3 is having the highest value of SI, which is selected as candidate bus. D-STATCOM is placed by assuming voltage at 3rd bus as 1pu. The current and reactive power to be injected is calculated. The load flow analysis is carried out by using the injected reactive power. The result shows the improvement of voltage profile. The bus voltage increased to 0.9358 from 0.8076 which is minimum before placing D-STATCOM

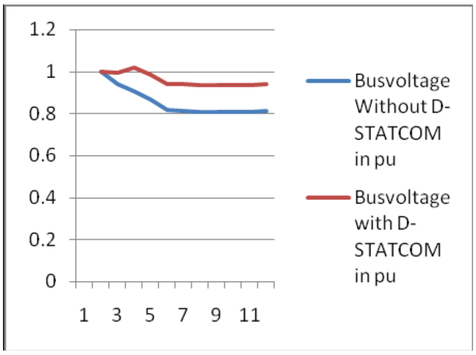

Fig.8. Bus voltage profile for Karumathur Feeder

9. CONCLUSION

The proposed work explains about a method which is used to improve the voltage performance of feeders in a substation and hence reduce the power loss. Sweep algorithm is used to determine the bus voltage and power loss in IEEE12, IEEE34 bus and distribution feeders namely Karumathur , Gandhinagar, Thenpalanji, Kannanur and average voltage of buses in the buses are 0.9653 pu, 0.8645 and feeders are 0.8529 pu , 0.8670 pu,0.9903 pu, 0.6126 pu respectively. The power losses for the IEEE buses are 19.7 KW, 131.6234 KW and feeders are 925.2 KW, 569 KW, 43.2

KW, 7776 KW, as respectively. This work presents an efficient approach for the placement of D-STATCOM in radial distribution system. Voltage stability index values for all the buses are determined to find the optimal bus which is selected as candidate bus for placement of DSTATCOM.The D-STATCOM is modelled by calculating injected reactive power for different reference voltages. Particle swarm optimization algorithm is used to find sizing of D-STATCOM. The resultant reactive power for IEEE12 bus is -92.3716 KVAR, IEEE34 bus is -448.1481 KVAR and Karumathar is 1KVAr, Gandhinagar 0.047KVAr ,Thenpalanji 0.1609KVAr, Kannanur 150.4478 KVAr. Again, the load flow analysis is performed by compensating the reactive power and voltage phase angle. The improved bus voltage for IEEE12 bus is 0.9655, IEEE34 bus is 0.9140 pu and Karumathur is 0.9609 pu, Gandhinagar 0.9259pu, Thenpalanji 0.9907 pu, Kannanur 0.9440 pu. The reduced power losses for the IEEE12,IEEE34 buses are 12.4 KW, 94.0341 KW and feeders are 320 KW, 43.2 KW, 388.8 KW, and 6494 KW respectively. The result shows the improvement in voltage profile and reduction in power losses. In future, ANN or Fuzzy logic could be used to adjust the rating of DSTATCOM for variations in load or any contingency cases.

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