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Co-Ordinated Control of D-STATCOMS in Radial Distribution System

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ABSTRACT: In the proposed work an effective method for minimization of power losses and voltages set to limits by placing D-STATCOMS (distribution static compensators) in radial distribution system based on voltage stability index. Optimal location of D-STATCOMS is found by calculating the voltage stability index at all the buses. Two most unstable buses are considered and co-ordinated with the two D-STATCOMS.The total rating is divided among those two bus locations to minimize the losses and maximize number of buseswith stable voltages. D-STATCOM is considered as a fixed capacitor injecting reactive power equal to its maximum rating and considered as a negative constant reactive power. Major advantage is improved speed of response and capacity for transient over load.

KEYWORDS: D-STATCOM; Radial distribution system; Voltage stability index (VSI); Optimal location; Optimal size; Reactive power compensation.

I.INTRODUCTION

In most of the applications the controllability is used to avoid cost intensive or landscape requiring extensions of power systems, for instance like upgrades or additions of substations and power lines. FACTS-devices provide a better adaptation to varying operational conditions and improve the usage of existing installations. When the STATCOM is used in distribution system it is called as a D-STATCOM (distribution –STATCOM) in power distribution networks. Distribution Static Compensator (D-STATCOM) has the capacity to overcome the certain drawbacks by providing precise control and fast response during transient and steady-state.D-STATCOM exhibits high speed control over reactive power to provide voltage stabilization, flicker suppression, and other types of system control. In utility applications, a D-STATCOM provides leading or lagging reactive power to achieve system stability during transient conditions.

Figure 1 illustrates single line diagram of the voltage source converter based D-STATCOM.A small lag of the converter voltage with respect to the voltage at the PCC causes real power to flow from the power system to the STATCOM, while the real power is transferred from the STATCOM to the power system by controlling the converter voltage so that it leads the voltage at the PCC

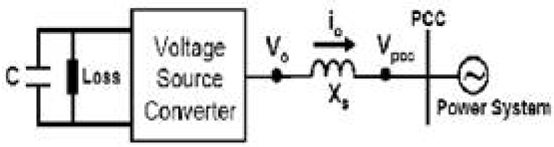

Figure 1: single line daigram of the voltage source converter based D-STATCOM

Initial application of DSTATCOM (using GTO devices) was primarily for the control of (fundamental frequency) reactive power control and voltage regulation. SVCS have been applied for this purpose earlier. A DSTATCOM has obvious advantages over a SVC. A major advantage relates to the improved speed of response, capacity for transient overlap (up to one second) in addition to the improved performance at reduced voltages.

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II. DISTRIBUTION SYSTEM LOAD FLOW SOLUTION

Load flow analysis [1-2] is a very important and it is the basic tool in the field of power system engineering. At the time of planning and design stages as well as during the operation stages of the power system and distribution automation.

The bus current injection at kth iteration is given by the following equation[3].

$$I_i^k = \left(\frac{S_i^{sch}}{v_i^k} \right)^* \tag{1}$$

Where,

S_i^{sch} = scheduled complex power at ithbus.

v_i^k = The bus i voltage at kth iteration.

I_i^K =The bus i current at kth iteration

For understanding the load flow procedure clearly here 6 bus radial distribution systems has been discussed using following equations.

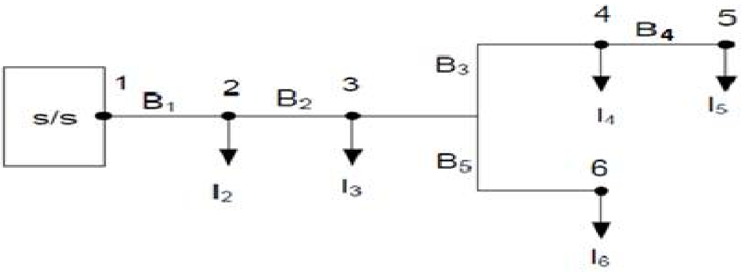

Figure 2: 6 node radial distribution system

A direct approach concept is designed based on the two derived matrices which are the bus-injection to branch-current matrix BIBC and the branch current to bus-voltage matrix BCBV.

Bus-Injection to Branch Current (BIBC) Matrix[1]
Figure 2[3] depicts a simple distribution system that is used as a case study for designing the relationship matrix.

a) Apply the function of equivalent current injection to formulate the branch current. By Referring to Figure 2, the branch currents can be expressed as
B1=I2+I3+I4+I5+I6
B2=I3+I4+I5+I6
B3=I4+I5
B4=I5
B5=I6

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Vol. 5, Issue 11, November 2016

b) The relation between BIBC can be expressed by

$$\begin{bmatrix} B_1 \\ B_2 \\ B_3 \\ B_4 \\ B_5 \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 & 1 & 1 \\ 0 & 1 & 1 & 1 & 1 \\ 0 & 0 & 1 & 1 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} I_2 \\ I_3 \\ I_4 \\ I_5 \\ I_6 \end{bmatrix} \quad (2)$$

c) The matrix of equation (2) can be expressed as in equation (3)

$$[B] = [BIBC][I] \quad (3)$$

Branch Current to Bus Voltage (BCBV) Matrix[1]

The relationship between branch currents and bus voltages for the network shown in Figure 2 can be constructed based on the concept of Kirchhoff's Voltage Law (KVL)[1]. The procedure used to determine the BCBV is described in the following steps.

Step 1: Apply the KVL to a six bus radial distribution system shown in Figure 2. Bus voltage can be expressed as

$$V_j = V_i - B_i Z_{ij} \quad (4)$$

Where, V_i is the voltage at bus i, V_j is the voltage of bus j. B_i is the branch current between bus i and j and Z_{ij} is the line impedance between bus i and bus j.

Step 2: The relation between branch currents and bus voltages can be expressed as

$$\begin{bmatrix} V_1 \\ V_1 \\ V_1 \\ V_1 \\ V_1 \end{bmatrix} - \begin{bmatrix} V_2 \\ V_3 \\ V_4 \\ V_5 \\ V_6 \end{bmatrix} = \begin{bmatrix} Z_{12} & 0 & 0 & 0 & 0 \\ Z_{12} & Z_{23} & 0 & 0 & 0 \\ Z_{12} & Z_{23} & Z_{34} & 0 & 0 \\ Z_{12} & Z_{23} & Z_{34} & Z_{45} & 0 \\ Z_{12} & Z_{23} & 0 & 0 & Z_{36} \end{bmatrix} \begin{bmatrix} B_1 \\ B_2 \\ B_3 \\ B_4 \\ B_5 \end{bmatrix} \quad (5)$$

Equation (5) can be expressed as in equation (6)

$$[\Delta V] = [BCBV][B] \quad (6)$$

Calculate the voltage mismatch using equation (6). The above equation can also be expressed as

$$[\Delta V] = [BCBV][BIBC][I] = [DLF][I] \quad (7)$$

Where DLF is a distribution load flow

$$[DLF] = [BIBC][BCBV] \quad (8)$$

a) Calculate the bus voltage magnitude of each bus by using below equation (9)

$$[V_i^k] = [V_1] - [DLF][I] \quad (9)$$

Where, V_1 is the slack bus and its magnitude is 1 p.u

b) After getting voltage magnitudes at all the buses, currents can be found by using equation (10).

$$I_{line} = (V_{frombus} - V_{tobus}) / (Z_{(j,j)}) \quad (10)$$

Losses can be calculated as shown below

$S_{send} = V_{frombus}$ *conj (I_{line}) (11)

$S_{to} = V_{tobus}$* conj (I_{line}) (12)

$S_{loss} = S_{send}$(j, 1) – S_{to}(j, 1) (13)

Total Loss = Total Loss + S_{loss}(j, 1) (14)

Repeat above steps for all lines of system and real part of total loss will give active power loss and imaginary part of total loss will give total reactive power loss of the system.

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III. VOLTAGE STABILITY INDEX

Optimal location of D-STATCOMS is found by calculating the voltage stability index at all the buses [3-5]. figure 3 [3] shows single line diagram of a two bus radial distribution system where $V_m$and V_n are sending end and receiving end voltages respectively, $I_m$is branch current, R_m&$X_m$are branch resistance and reactance respectively,P_m&$Q_m$are real power and reactive power at sending end,P_n&$Q_n$are real power and reactive power at receiving end.

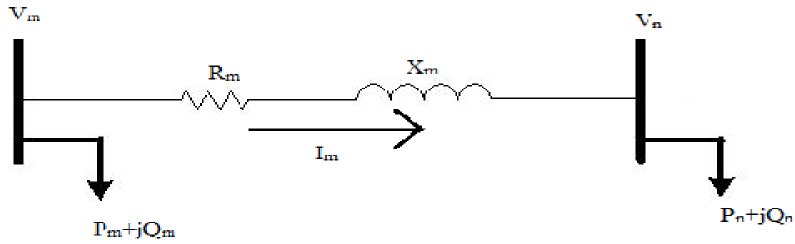

Figure 3: single line of 2-bus distribution system

The expression for voltage stability index is derived as follows. From figure 3[3]the current in branch is given by

$$I_m = \frac{V_m\angle\theta_m - V_n\angle\theta_n}{R_m + jX_m} \quad (15)$$

Here θ_m and θ_n are the phase angles at V_m and V_n respectively.
The complex power is expressed as

$$S = VI^* \quad (16)$$

Which gives,

$$I_m = \frac{P_n - jQ_n}{V_n^*} = \frac{P_n - jQ_n}{V_n\angle -\theta_n} \quad (17)$$

On equating equations (15) and (17) and cross multiplying , we can get

$$V_m V_n \angle(\theta_m - \theta_n) - V_n^{\ 2} = P_n R_m + Q_n X_m - j(R_m Q_n - P_n X_m) \quad (18)$$

By equating real and imaginary parts and assuming $(\theta_m - \theta_n) \cong 0$, because voltage phase angles are almost equal at V_m and V_n in radial distribution system. So that the difference is negligible or approximately equal to zero in radial distribution system,then

$$V_m V_n - V_n^{\ 2} = P_n R_m + Q_n X_m \quad (19)$$

$$R_m Q_n - P_n X_m = 0 \Rightarrow X_m = \frac{R_m Q_n}{P_n} \quad (20)$$

On substituting equation (20) in equation (19) and arranging, we get

$$V_n^{\ 2} - V_m V_n + \frac{R_m(P_n^{\ 2} + Q_n^{\ 2})}{P_n} = 0 \quad (21)$$

The roots of the above equation (21) to be real,

$$V_m^{\ 2} - \frac{4R_m(P_n^{\ 2} + Q_n^{\ 2})}{P_n} \geq 0 \quad (22)$$

$$\Rightarrow \frac{4R_m(P_n^{\ 2} + Q_n^{\ 2})}{P_n V_m^{\ 2}} \leq 1 \quad (23)$$

From that voltage stability index is defined as

$$VSI = \frac{4R_m(P_n^{\ 2} + Q_n^{\ 2})}{P_n V_m^{\ 2}} \quad (24)$$

Voltage stability is found for all the buses. For stability voltage stability index value should be ≤ 1. the bus which is having maximum value of voltage stability index is treated as most unstable bus or candidate bus, and the second highest value of voltage stability index is treated as next unstable bus.

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IV. OPTIMAL SIZING AND PLACING OF D-STATCOMS

Steady state modeling of D-STATCOM [3, 5-7]

The single line diagram of two buses of a distribution system with D-STATCOM is shown in figure 4. In this paper D-STATCOM is used to improve voltage profile, reduce losses in steady state condition and injects only reactive power to the power system. Consequently, $I_{D-STATCOM}$ must be kept in quadrature with voltage of the system. The schematic diagram of buses m and n of the distribution systems, when D-STATCOM is installed for voltage regulation in bus n, is as shown in figure 4 [7]the phasor diagram of these buses with D-STATCOM effects is shown in figure 5 [7] voltage of bus n changes from V_n to V_n' when D-STATCOM is placed .for simplicity, assume voltage at bus $V_n'$is 1 p.u.,voltage at bus V_m' is assumed to nearer to 1 p.u., the angle of voltage V_m' is assumed as zero because the angle at V_m' from load flow is nearer to zero. The current in the line is changed from $I_m$to I_m'.

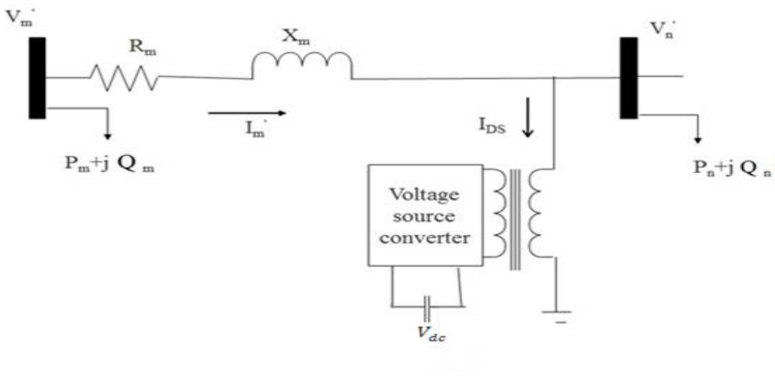

Figure 4: single line daigram of 2-bus distribution system with D-STATCOM

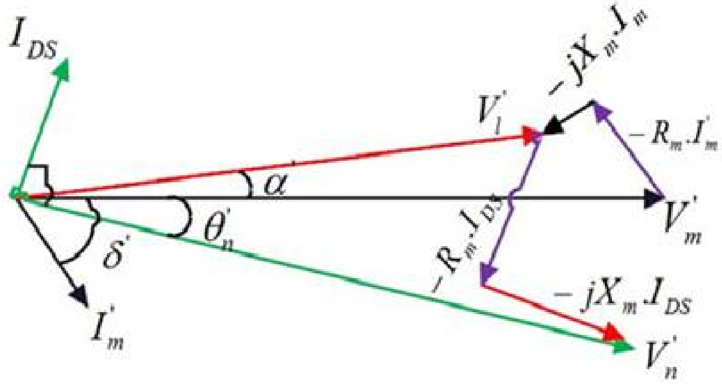

Figure 5: Phasor daigram of voltage and currents of the system shown in figure 4

The expression for voltage and current for figure 4 can be written as

$$V_n'\angle\theta_n' = V_m'\angle\theta_m' - (R_m + jX_m)(I_m\angle\delta) - (R_m + jX_m)\left(I_{DS}\angle(\tfrac{\pi}{2} + \theta_n')\right) \quad (25)$$

Hereθ_m' , θ_n'&δ are the phase angles of V_m' , V_n'&I_m respectively.

Here $I_{DS}\angle(\frac{\pi}{2} + \theta_n')$ injected current by D-STATCOM

$V_n'\angle\theta_n'$ Voltage of bus n after D-STATCOM installation

$V_m'\angle\theta_m'$ Voltage of bus m after D-STATCOM installation

$I_m'\angle\delta'$ Current in the line after D-STATCOM installation

Voltage $V_m\angle\theta_m$and current $I_m\angle\delta$ are derived from the load flow calculations. Separating real and imaginary parts of the equation.

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Vol. 5, Issue 11, November 2016

$$V_n' \cos\theta_n' = V_m' \cos\theta_m' - I_m \mathrm{Rm}\cos\delta + I_m X_m \sin\delta - I_{DS}\mathrm{Rm}\cos(\tfrac{\pi}{2}+\theta_n') + I_{DS}X_m \sin(\tfrac{\pi}{2}+\theta_n') \quad (26)$$

$$V_n' \sin\theta_n' = V_m' \sin\theta_m' - I_m \mathrm{Rm}\sin\delta - I_m X_m \cos\delta - I_{DS}X_m\cos(\tfrac{\pi}{2}+\theta_n') - I_{DS}\mathrm{Rm}\sin(\tfrac{\pi}{2}+\theta_n') \quad (27)$$

$h1 = V_m' \cos\theta_m' - I_m \mathrm{Rm}\cos\delta + I_m X_m \sin\delta$ (28)
$h2 = V_m' \sin\theta_m' - I_m \mathrm{Rm}\sin\delta - I_m X_m \cos\delta$ (29)
$h3 = -X_m$ (30)
$h4 = -\mathrm{Rm}$ (31)
$h5 = V_n'$ (32)
$x_1 = I_{DS}$ (33)
$x_2 = \theta_n'$ (34)
Considering $\sin x_2 = x$

$$(k_1^2 + k_2^2)x^2 + (2k_1 b c_1)x + \left(h_5{}^2 h_3^2 - k_2^2\right) = 0 \quad (35)$$

Where

$$k1 = h_1 h_4 - h_2 h_3$$
$$k_2 = h_1 h_3 + h_2 h_4$$

Therefore

$$x = \frac{-B \pm \sqrt{D}}{2A} \quad (36)$$

Where:

$$D = B^2 - 4AC$$
$$B = 2k_1 h_5 h_3$$
$$A = k_1^2 + k_2^2$$
$$C = h_5{}^2 h_3^2 - k_2^2$$

After finding$x$; $x_2 = \theta_n'$(angle of corrected voltage) is defined as:

$$\theta_n' = x_2 = \sin^{-1}(x) \quad (37)$$

And $x_1 = I_{DS}$is defined from above equation (33)

It can be seen from equation (36) that there are two roots for x and therefore, two values are calculated for x_{11} andx_{22}, but one of them is acceptable. To determine the correct answer, these roots are examined under the following boundary condition in the load flow results:

If $I_{DS} = 0$ $V_n' = \mathrm{Vn}$&$\theta_n' = \theta_n$

After testing this condition on load flow results, $x = \frac{-B+\sqrt{D}}{2A}$ is seleted as the correct answer for equation (35) and then x_2 and x_1 are calculated from (37) and (33), respectively.

Finally reactive power injected by D-STATCOM can be written as:

$$j.Q_{D-STATCOM} = \overrightarrow{V_n'} \cdot \overrightarrow{I}^{*}_{DS} \quad (38)$$

Where:

$$\overrightarrow{V_n'} = V_n' \angle \theta_n'$$

$\angle I_{DS} = \frac{\pi}{2} + \theta_n'$

$$\overrightarrow{I_{DS}} = I_{DS}\angle(\frac{\pi}{2} + \theta_n')$$

Here symbol "*" denotes conjugate of complex variable.

V. ALGORITHM

Step 1: Read line and bus data for radial distribution system.
Step 2: Perform the load flow to find voltages at all the buses and losses for all the branches.
Step 3: Find voltage stability index at all the buses using equation (24).
Step 4: Find maximum value of voltage stability index bus.

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Vol. 5, Issue 11, November 2016

Step 5: Find I_{DS} , voltage phase angle and injected reactive power by assuming voltage at the most unstable bus as 1 p.u. using equations (33),(37), and (38).
Step 6: Co-ordinate the two most unstable buses to minimize losses.
Step 7: Run the load flow by compensating the reactive powers and voltage phase angle and find voltage and power losses.
Step 7: End

VI. RESULTS AND DISCUSSION

Table 1: bus voltage magnitude & Bus voltage angle without D-STATCOM for IEEE 33-bus

Bus no.	Bus voltage magnitude	Bus voltage angle
1	1.00000	0.00000
2	0.99703	0.01448
3	0.98294	0.09605
4	0.97546	0.16166
5	0.96806	0.22830
6	0.94966	0.13389
7	0.94617	-0.09643
8	0.94133	-0.06036
9	0.93506	-0.13343
10	0.92925	-0.19595
11	0.92839	-0.18870
12	0.92688	-0.17849
13	0.92076	-0.26981
14	0.91850	-0.34849
15	0.91708	-0.38617
16	0.91572	-0.40942
17	0.91369	-0.48669
18	0.91308	-0.49628
19	0.99650	0.00365
20	0.99293	-0.06333
21	0.99222	-0.08268
22	0.99158	-0.10303
23	0.97935	0.06509
24	0.97268	-0.02365
25	0.96936	-0.06735
26	0.94773	0.17335
27	0.94515	0.22844
28	0.93371	0.31139
29	0.92549	0.38929
30	0.92193	0.49457
31	0.91777	0.41016
32	0.91686	0.38712
33	0.91657	0.37939

Table 2: voltage stability index at all the buses

Bus no.	Voltage stability index
2	0.0003
3	0.0014
4	0.0017
5	0.0008
6	0.0015
7	0.0013
8	0.0050
9	0.0020
10	0.0020
11	0.0004
12	0.0009
13	0.0035
14	0.0028
15	0.0011
16	0.0015
17	0.0026
18	0.0024
19	0.0004
20	0.0041
21	0.0011
22	0.0019
23	0.0014
24	0.0122
25	**0.0123**
26	0.0004
27	0.0006
28	0.0020
29	0.0038
30	**0.0298**
31	0.0053
32	0.0024
33	0.0009

Table3: Bus voltage magnitude & bus voltage angle with D-STATCOM for IEEE 33-bus

Bus no.	Bus voltage magnitude	Bus voltage angle
1	1.00000	0.00000
2	0.99766	-0.05121
3	0.98693	-0.32592
4	0.98131	-0.45731
5	0.97585	-0.59838
6	0.96441	-1.13990
7	0.96098	-1.36309
8	0.95621	-1.32817
9	0.95005	-1.39898
10	0.94433	-1.45953
11	0.94348	-1.45252
12	0.94200	-1.44264
13	0.93598	-1.53104
14	0.93375	-1.60718
15	0.93237	-1.64364
16	0.93102	-1.66614
17	0.92903	-1.74088
18	0.92843	-1.75015
19	0.99713	-0.06203
20	0.99356	-0.12892
21	0.99285	-0.14826
22	0.99222	-0.16858
23	0.98441	-0.44536
24	0.98019	-0.71081
25	0.97928	-0.93213
26	0.96350	-1.21478
27	0.96237	-1.32023
28	0.96003	-1.83305
29	0.95867	-2.21126
30	0.95768	-2.39904
31	0.95368	-2.47724
32	0.95279	-2.49858
33	0.95252	-2.50574

The line and load data of IEEE 33 bus distribution system is taken from reference [6]. Table 4 shows that co-ordinated D-STATCOMS placement of size 1.4453 MVAR and 0.5345 MVAR using voltage stability index at 30th and 25th buses respectively. The active power losses reduce by 61.075 KW from 202.669 KW to 141.594 KW and reactive

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power losses reduce by 39.492 KW from 135.185 KVAR to 95.693 KVA. Number of buses having under/over voltage problem reduces to 9 after D-STATCOMS placement as compared to 21 without D-STATCOM. The minimum voltage increases from 0.91308 p.u. to 0.92843 p.u. at 18th bus.

Table 4: Without and with D-STATCOMS Placement in radial distribution system with constant power load

Description	Without D-STATCOM	With co-ordinated D-STATCOMS placement	percentage (%) reduction
Total active power load in KW	3715	3715	---
Total reactive power load in KVAR	2300	2300	---
No of buses having under/over voltage problem	21	9	57.14
Minimum voltage	0.91308	0.92843	---
Optimal location of D-STATCOM	---	30th and 25th buses	---
Optimal size of D-STATCOM In MVAR	---	1.9799	---
Total active power losses in KW	202.669	141.594	30.13
Total reactive power line losses in KVAR	135.185	95.693	29.21

Table 5: Co-ordination of D-STATCOMS

Percentage of D-STATCOM at 30th bus	Percentage D-STATCOM at 25th bus	Active power losses in KW	Reactive power losses in KVAR	No of buses having under/over voltage problem
0%	0%	202.669	135.185	21
100%	0%	161.649	110.464	10
90%	10%	151.237	102.799	9
80%	20%	144.328	97.70	9
75%	25%	142.197	96.138	9
73%	**27%**	**141.594**	**95.693**	**9**
70%	30%	140.957	95.221	10
60%	40%	141.168	95.364	13
50%	50%	145.008	98.173	15
40%	60%	152.530	103.686	15
30%	70%	163.79	111.944	16

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Table 6: Results & discussion

Parameters	**With co-ordinated D-STATCOMS placement**	Ref [3] results	Ref [5] results	Ref [6] results	Ref [8] Results
Active power loss before installation(KW)	**202.669**	210.99	201.8925	202.68	210.99
Active power loss after installation(KW)	**141.594**	169.79	140.5936	171.81	157.48
Reactive power loss before installation(KVAR)	**135.185**	143.032	----	----	143.03
Reactive power loss after installation(KVAR)	**95.693**	118.148	----	----	109.02
Optimal size of D-STATCOMS(MVAR)	**1.9799**	1.993	3.386	0.9624	1.691
Optimal location of D-STATCOMS	**30th and 25th buses**	30th bus	30th bus	12th bus	29th bus
% active loss reduction	**30.13**	19.52	30.36	15.23	25.36
% reactive loss reduction	**29.21**	17.39	----	----	23.77
No of buses having under/over voltage problem after D-STATCOM placement	**9**	10	0	12	11
Loss saving(KW)	**61.075**	41.02	61.29	30.87	53.51
Annual energy saving(KWh)	**535017**	360912	536978	270421	468747.6

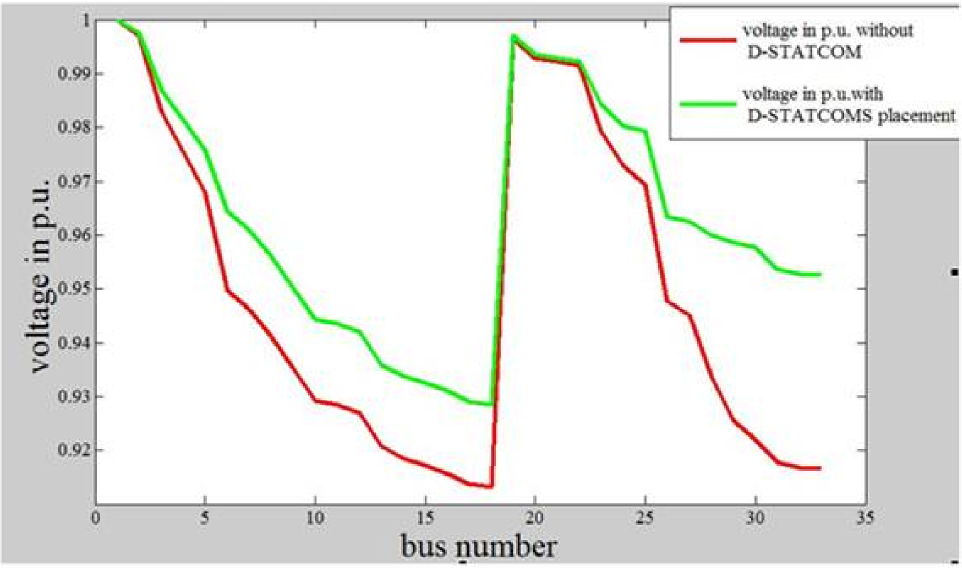

Figure 6: Voltage graphs with and without D-STATCOMS

From figure 6, conclude that the voltage at each node is improved with the placement of co-ordinated D-STATCOMS in radial distribution system.

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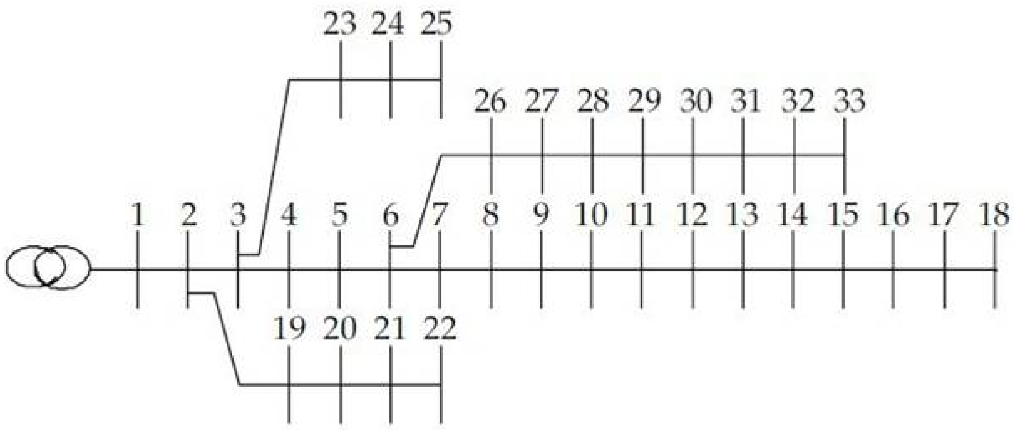

Figure 7: 33 bus radial distribution system[3]

VII.CONCLUSION

In this paper, an effective method for the placement of D-STATCOMS in radial distribution system based on voltage stability index is presented. The D-STATCOMS rating and direction of reactive power injection are derived and discussed analytically and mathematically by using phasor diagram method. The pro-posed model for co-ordinated D-STATCOMS is applied to load flow calculations in 33 bus test system. The load flow analysis is carried out by compensating the reactive power and voltage phase angle at the unstable buses. The result shows the improvement in voltage profile and reduction in active and reactive power losses. The D-STATCOMS in distribution system can play an important role for better voltage profile and reducing losses in the system thereby increasing annual energy saving in the distribution systems. This study can be helpful for better distribution system planning with D-STATCOMS for different issues like reactive power management, loss profile management and distribution system pricing.

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