OPTIMAL PLACEMENT OF D-STATCOM AND LOAD FLOW ANALYSIS OF RADIAL DISTRIBUTION NETWORKS

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Abstract:

This paper presents the modeling of shunt Distribution FACT device in load flow analysis for the steady state voltage compensation and loss minimizations. For this purpose, Distribution STATCOM (D-STATCOM) is considered as shunt compensator. An accurate model for this device is derived to use in load flow analysis. The rating of this device as well as direction of reactive power injection required to compensate voltage to the desired value (1 p.u) are derived and discussed analytically and mathematically using phasor diagrams. Since performance of D-STATCOM varies when it reach to the maximum capacity, modeling of this compensator in the maximum rating of reactive power injection are derived and discussed. The validity of proposed model for fixed compensation and compensation for fixed voltage is examined using MATLAB coding for two IEEE standard distribution systems consisting of 33 and 69 nodes respectively. The best location of D-STATCOM using Rate of under Voltage Mitigation node (RUVMN) in the distribution network is determined.

Key words: D-STATCOM, Fixed compensation, Fixed voltage, RUVMN, load flow.

1. Introduction

An electric distribution system is part of an electric system between the bulk power source or sources and the consumers' service switches. The bulk power sources are located in or near the load area to be served by the distribution system and may be either generating stations or power substations supplied over transmission lines. With an increase in load demand, burden on lines and the voltage level is challenged. Now a day's maintaining voltage magnitude at an acceptable range is one of the major system constraints. One of the classical methods to solve this is to place shunt capacitor in line [Baran et al.(1999)]. But the reactive power provided by the shunt capacitor is bus voltage. This may reduce its effectiveness in high and low voltages. Another problem related to shunt capacitor is that they resonate when got tuned with system.

Although the concept of FACTS was developed originally for transmission network; this has been extended since last 10 years for improvement of Power Quality(PQ) in distribution systems operating at low or medium voltages. Apart from all other technical advances, these FACTS devices respond quickly to the changes in network condition unlike to shunt capacitor even for high distribution voltages. Distribution STATCOM (D-STATCOM) is a shunt connected voltage source converter which has been utilized to compensate bus voltages or lagging VARs.

D-STATCOM is a shunt device that injects or absorbs both active and reactive powers which are shown in Fig. 1(a) and 1(b). In Fig. 1(a), it can be seen that D-STATCOM consists of energy storage and voltage source converter. In this model, D-STATCOM is capable of injecting active power in addition to reactive power. Since energy storage has a capacity limit, it is not capable to inject active power for a long term for voltage regulation purpose. Therefore, for the steady-state application, D-STATCOM consists of a small dc capacitor and a voltage source converter and the steady-state power exchange between D-STATCOM and the ac system is reactive power which is shown in Fig. 1(b).

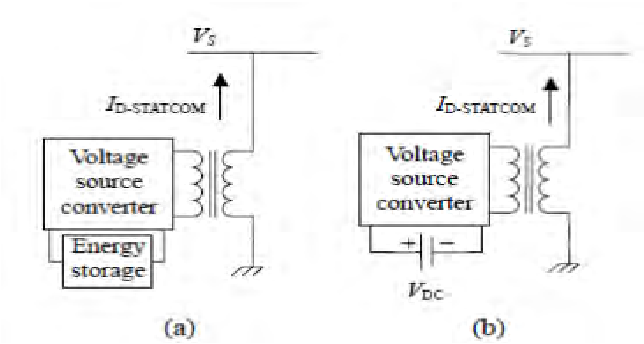

Fig. 1. A typical D-STATCOM model (a) Active and reactive power exchange (b) Only reactive power exchange

2. Load Flow Solution of Radial Distribution Network

The proposed method is developed based on two derived matrices, the bus-injection to branch-current matrix and the Branch current to bus-voltage matrix, and equivalent current injections. In this section, the development procedure will be in detail. For distribution networks, the equivalent- current-injection based model is more practical [Shirmohammadi et al.(1988)]. For bus i, the complex load Si is expressed by

$$S_i = P_i + jQ_i \qquad (1)$$

Where i= 1, 2, ... N

And the corresponding equivalent current injection at the –kthiteration of solution is

$$\mathbf{I_i^k = I_i^k(V_i^k) + j\, I_i^k(V_i^k) = (P_i + jQ_i/V_i^k)^*} \qquad (2)$$

Where

V_i^k and I_i^k are the bus voltages and equivalent current injection of bus i at kth iteration respectively.

2.1 *BIBC matrix development*

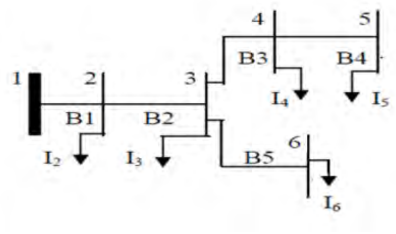

Fig. 2. Simple distribution system

A simple distribution network shown in fig.1 is used as an example the current equations are obtained from the Eq, (3) .The relationship between bus currents and branch currents can be obtained by applying Kirchhoff's current law (KCL) to the distribution network. Using the algorithm of finding the nodes beyond all branches proposed by Gosh et al. The branch currents then be formulated as functions of equivalent current injections for example branch currents B1, B and B5 can be expressed as

$$\left.\begin{aligned} &B1= I2+I3+I4+I5+I6 \\ &B3=I4+I5 \\ &B5= I6 \end{aligned}\right\} \tag{3}$$

Therefore the relationship between the bus current injections and branch currents can be expressed as

$$\begin{bmatrix} B1 \\ B2 \\ B3 \\ B4 \\ B5 \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 & 1 & 1 \\ 0 & 1 & 1 & 1 & 1 \\ 0 & 0 & 1 & 1 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} I2 \\ I3 \\ I4 \\ I5 \\ I6 \end{bmatrix} \tag{4}$$

Eq (4) can be expressed in general form as

$$[B]= [BIBC][I] \tag{5}$$

Where BIBC is a bus injection to branch current matrix, the BIBC matrix is a upper triangular matrix and contains values of 0 and 1 only.

The receiving end bus voltages are found by forward sweep through the ladder network using the generalized equation as

$$V(m2)=V(m1)-I(jj)Z(jj) \tag{6}$$

Where

m1, m2 are the sending and receiving ends and

jj is the branch number

The real and reactive power losses of branch jj are given by

$$P\text{-}LOSS=|I(jj)|^{2*}R(jj) \tag{7}$$

$$Q\text{-}LOSS=|I(jj)|^{2}*X(jj) \tag{8}$$

3. Steady-State Modeling of D-STATCOM

Consider two bus system which is shown in Fig. 3

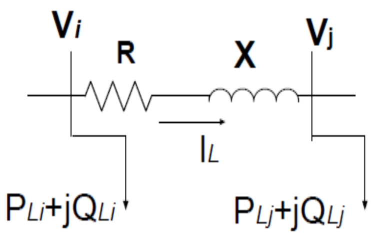

Fig. 3. single line diagram of two buses of a distribution system

To analyze it, it is assumed that one of the bus reference bus and other has a low voltage profile than that of the reference bus. Here Vi is the reference bus and Vj is the desired bus for compensation. Now it is desired to compensate the bus voltage of Vj to 1p.u by using D-STATCOM. The phasor diagram of the single line diagram (Fig. 3) is shown in Fig. 4

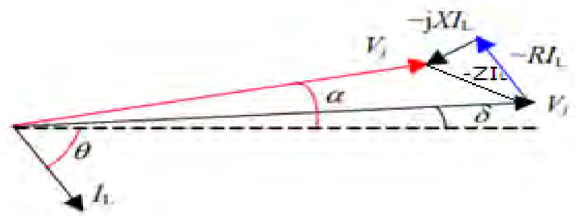

Fig. 4. Phasor diagram of voltages and current of the system shown in Fig. 3

From this phasor diagram (Fig. 4), it is drawn that,

$Vj\angle\alpha = Vi\angle\delta - ZI_L\angle\theta$ (9)

Where $Vj\angle\alpha$ and $Vi\angle\delta$ are the voltage of buses *j* and *i* before compensation respectively,

Z=*R*+ *j X* is the impedance between buses *i* and *j*,

$I_L\angle\theta$ is the current flow in line.

Voltage $Vi\angle\delta$ and current $I_L\angle\theta$ are the values which are derived from the load flow calculations. Fig. 5 gives a better idea of placing D-STATCOM in a distribution system for steady state analysis.

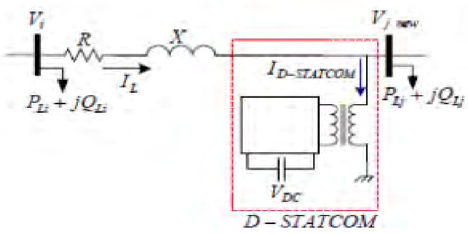

Fig. 5. Single line diagram of two buses of a distribution systems after placement of D-STATCOM

As noted earlier, in this paper, D-STATCOM is used for voltage regulation in the steady state condition and can inject only reactive power to the system. Consequently, $I_{D\ STATCOM}$ must be kept in quadrature with voltage of the system. By installing D-STATCOM in distribution system, all node voltages, especially the neighboring nodes of D-STATCOM location, and braches current of the network change in the steady-state condition. The schematic diagram of buses i and *j* of the distribution system, when D-STATCOM is installed for voltage regulation in bus *j*, is shown in Fig.5. Phasor diagram of these buses with D-STATCOM at bus j is shown in Fig. 6. Voltage of bus j changes from V_j to $V_{j\ new}$ when D-STATCOM is placed.

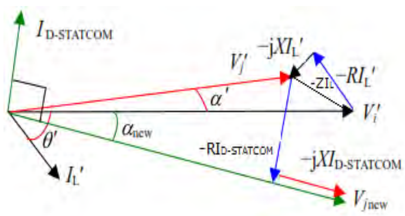

Fig. 6. Phasor diagram of voltages and current of the system shown in Fig. 5

From the phasor diagram (fig.6),

$$\angle I_{DSTATCOM} = \frac{\pi}{2} + \alpha_{new} \ , \alpha_{new} < 0 \quad (10)$$

$$V_{jnew}\angle\alpha_{new} = V_i'\angle\delta' - (R + jX)I_L'\angle\theta' - (R + jX)I_{DSTATCOM}\angle\left(\alpha_{new} + \frac{\pi}{2}\right). \quad (11)$$

$V_{jnew}\angle\alpha_{new}$ is the voltage of bus *j* after compensation by DSTATCOM. $V'i\angle\delta'$ is the voltage of bus *i* after compensation. The value of $I'_L\angle\theta'$ is obtained from load flow calculations.

Separating the real and imaginary parts of Eq(11) yields

$$V_{j\,new}\cos\alpha_{new} = Re(V'_i\angle\delta) + XI_{D-STATCOM}\sin(\alpha_{new}+\tfrac{\pi}{2}) - Re(ZI'_L\angle\theta') - RI_{D-STATCOM}\cos(\alpha_{new}+\tfrac{\pi}{2})$$

$$V_{j\,new}\sin\alpha_{new} = Im(V'_i\angle\delta') - XI_{D-STATCOM}\cos(\alpha_{new}+\tfrac{\pi}{2}) - Im(ZI'_L\angle\theta') - RI_{D-STATCOM}\sin(\alpha_{new}+\tfrac{\pi}{2}) \quad (13)$$

Further more these two equations can be modified using the following notations

$$a_1 = Re(V'_i\angle\delta') - Re(ZI'_L\angle\theta')$$

$$a_2 = Im(V'_i\angle\delta') - Im(ZI'_L\angle\theta')$$

$$\left.\begin{aligned} b &= V_{jnew} \\ c_1 &= -R \\ c_2 &= -X \\ x_1 &= I_{D-STATCOM} \\ x_2 &= \alpha_{new} \end{aligned}\right\} \quad (14)$$

Substitute Eq (14) in Eq (12) and (13) , one can get Eq (15) and (16) respectively

$$b\cos x_2 = a_1 - c_1x_1\sin x_2 - c_2x_1\cos x_2 \quad (15)$$

$$b\sin x_2 = a_2 - c_2x_1\sin x_2 + c_1x_1\cos x_2 \quad (16)$$

where
a_1, a_2, $c_1 and c_2$ are constants
b is the magnitude of compensated voltage (1 p.u.) and
x_1, x_2 are variables to be determined.
From eq(15), it can be shown that

$$x_1 = \frac{b\cos(x_2) - a_1}{-c_1\sin(x_2) - c_2\cos(x_2)} \quad (17)$$

From eq(16), it can be shownthat

$$x_1 = \frac{b\sin(x_2) - a_2}{-c_2\sin(x_2) + c_1\cos(x_2)} \quad (18)$$

Now by equating (17) and (18) to eliminating x_1, one can get

$$(a_1c_2 - a_2c_1)\sin x_2 + (-a_1c_1 - a_2c_2)\cos x_2 + bc_1 = 0 \quad (19)$$

Considering $x = sinx_2$, following equations are derived

$$(K_1^{\,2}+K_2^{\,2})x^2+(2k_1bc_1)x+(b^2c_1^{\,2}-k_2^{\,2})=0 \qquad (20)$$

$$k_1 = a_1c_2 - a_2c_1$$
$$k_2 = a_1c_1 + a_2c_2$$

$$x=\frac{-B\pm\sqrt{d}}{2A}$$

Where

$$d = B^2 - 4AC$$
$$A = k_1^{\,2} + k_2^{\,2}$$
$$B = 2k_1bc_1$$
$$C = b^2c_1^{\,2} - k_2^{\,2}$$

From the roots of x, $\alpha_{new} = x2 = arc \sin x$ Substitute x_2 value either in eq (17) or (18) to get x_1 or $I_{D\text{-}STATCOM}$ value. Hence injected reactive power by DSTATCOM is given by

$$jQ_{D-STATCOM} = V_{j\ new}\, I^{*}_{D-STATCOM} \qquad (21)$$

$$\mathbf{V}_{j\ new} = V_{j\ new}\ \angle\alpha_{new} \qquad (22)$$

$$\mathbf{I}_{D-STATCOM} = \mathrm{I}_{D-STATCOM}\angle(\alpha_{new} + \tfrac{\pi}{2}) \qquad (23)$$

Reactive power supplied by DSTATCOM at bus j will improve voltage profile to desired value. (Preferably 1p.u) This compensation improves voltage profile of neighboring buses (if present) mostly the downstream buses.

4. Methods of compensation using D-STATCOM in Distribution Load flow

In this paper two compensation techniques are used by using DSTATCOM in distribution systems. They are fixed compensation and compensation for fixed voltage.

4.1 *Fixed compensation*

In the previous section, it is assumed that the voltage magnitude in node j(i.eV_{jnew}) is compensated to the specific value of 1 p.u and after that, the phase angle of voltage in node j(i.eα_{new}),injected current and reactive power by D-STATCOM are derived from Eq(17) & (21), respectively. If the reactive power requirement reaches to its maximum limit of DSTATCOM, it no longer regulates the voltage of node j in 1p.u at all. In this condition, D-STATCOM is considered as a fixed capacitor injecting reactive power equal to its maximum rating and considered as a negative constant reactive power load in node j.

4.2 *Compensation for fixed voltage*

For modeling D-STATCOM in load flow calculations, in any iteration in forward sweep, at first, it is assumed that the voltage magnitude of the compensated node is 1p.u. Then, the phase angle of compensated voltage and rating of injected reactive power by D-STATCOM are calculated from Eq (21). Then, the new voltage magnitude and phase angle of compensated node are utilized to determine voltage of D-STATCOM location nodes in the forward sweep of load flow. The updated voltage of nodes and injected reactive power by D-STATCOM are used to determine the load currents using Eq(2) in the next sweep of load flow. This procedure is continued until load flow is converged.

5. Rate of Under Voltage Mitigation Nodes (RUVMN)

RUVMN forms the criteria for selection of suitable buses for D-STATCOM placement. The higher the value of %RUVMN for a particular node, more is the chances of placing FACTS device on that bus. The percentage of RUVMN is given by

$$\%RUVMN = \frac{B_b - B_c}{B_t} * 100$$

Where
B_b = No.of buses which are out of constraint limit before compensation
B_c = No.of buses which are out of constraint limit remained after compensation)
B_t = Total no. of buses

6. Results

Two distribution systems consisting of IEEE 33 and IEEE 69 buses are considered to validate the proposed models associated with D-STATCOM device are applied to the load flow program. The results obtained in each case are summarized in this section.

6.1 *IEEE 33 bus test system*

The line data and load data [Yuan-Kang et al.(2010)] of the 12.66kv, 33-bus, 4 lateral radial distribution system are considered in this case. The results of load flow solution before D-STATCOM installation are presented in Table-1. It is assumed that the upper and lower limits of the voltage magnitude are 1.05 p.u and 0.95 p.u., respectively. It can be seen that 21 out of 33 nodes of distribution system (63.63%) have under voltage problem.

Table 1.Voltage magnitude and phase angle in 33-bus distribution system without D-STATCOM

Bus No	Voltage magnitude (p.u)	Phase angle (degree)	Bus No	Voltage magnitude (p.u)	Phase angle (degree)	Bus No	Voltage magnitude (p.u)	Phase angle (degree)
1	1	0	12	0.9456	-0.1713	23	0.9832	0.071
2	0.9975	0.0206	13	0.9396	-0.2626	24	0.9765	-0.0177
3	0.9867	0.1021	14	0.9374	-0.3414	25	0.9732	-0.0624
4	0.9817	0.1677	15	0.936	-0.3791	26	0.966	0.1795
5	0.9769	0.2344	16	0.9347	-0.4023	27	0.9635	0.2356
6	0.9679	0.1399	17	0.9327	-0.4796	28	0.9523	0.3186
7	0.9645	-0.0905	18	0.9321	-0.4892	29	0.9443	0.3965
8	0.9598	-0.0544	19	0.997	0.0097	30	0.9408	0.5018
9	0.9536	-0.1275	20	0.9934	-0.0573	31	0.9367	0.4174
10	0.9479	-0.1901	21	0.9927	-0.0766	32	0.9358	0.3944
11	0.9471	-0.1828	22	0.992	-0.097	33	0.9355	0.3866

In order to indicate and compare the effects of D-STATCOM in IEEE 33bus distribution system, RUVMN of distribution system is calculated for all the nodes by placing DSTATCOM at each node at a time for both fixed compensation with 2MVAR and compensation for fixed voltage (1 p.u) as shown in table 2 & table 3 respectively.

Table 2. RUVMN for Fixed Voltage D-STATCOM in 33 Bus radial distribution system

Node No	RUVMN %	Node No	RUVMN %
1	0	18	3.0303
2	6.0606	19	0
3	21.2121	20	0
4	33.3333	21	0
5	54.5455	22	0
6	60.6061	23	0
7	39.3939	24	0
8	36.3636	25	0
9	33.3333	26	27.2727
10	30.303	27	24.2424
11	27.2727	28	21.2121
12	24.2424	29	18.1818
13	21.2121	30	15.1515
14	18.1818	31	12.1212
15	12.1212	32	6.0606
16	9.0909	33	3.0303
17	6.0606		

Table 3. RUVMN for Fixed Compensation D-SATACOM in 33 Bus radial distribution system

Node No	RUVMN %	Node No	RUVMN %
1	0	18	45.4545
2	3.0303	19	3.0303
3	6.0606	20	0
4	12.1212	21	3.0303
5	15.1515	22	0
6	21.2121	23	6.0606
7	30.303	24	6.0606
8	33.3333	25	6.0606
9	48.4848	26	21.2121
10	48.4848	27	21.2121
11	48.4848	28	36.3636
12	48.4848	29	36.3636
13	48.4848	30	36.3636
14	48.4848	31	36.3636
15	45.4545	32	36.3636
16	45.4545	33	36.3636
17	45.4545		

Table 4. Voltages after Compensation by using Fixed Voltage and Fixed Compensation Method using D-STATCOM

Node No	Nodes where DSTATCOM is placed for Fixed Voltage compensation			Nodes where Fixed Compensation with 2MVAR		
	6	22	26	10	22	26
	V (p.u)	V (p.u)	V (p.u)	V (p.u)	V (p.u)	V (p.u)
1	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
2	0.9970	0.9969	0.9969	0.9969	0.9971	0.9975
3	0.9834	0.9828	0.9831	0.9828	0.983	0.9867
4	0.9762	0.9753	0.9758	0.9753	0.9755	0.9817
5	0.9692	0.9679	0.9686	0.9679	0.9681	0.9769
6	1.0000	0.9495	0.9507	0.9495	0.9497	0.9679
7	0.9967	0.946	0.9473	0.9460	0.9463	0.9645
8	0.9921	0.9411	0.9424	0.9411	0.9414	0.9598
9	0.9862	0.9349	0.9362	0.9349	0.9351	0.9536
10	0.9807	0.9291	0.9304	0.9291	0.9293	0.9479
11	0.9799	0.9282	0.9295	0.9282	0.9285	0.9471
12	0.9784	0.9267	0.928	0.9267	0.927	0.9456
13	0.9727	0.9206	0.9219	0.9206	0.9209	0.9396
14	0.9705	0.9183	0.9196	0.9183	0.9186	0.9374
15	0.9692	0.9169	0.9182	0.9169	0.9172	0.936
16	0.9679	0.9155	0.9169	0.9155	0.9158	0.9347
17	0.966	0.9135	0.9148	0.9135	0.9138	0.9327
18	0.9654	0.9129	0.9142	0.9129	0.9132	0.9321
19	0.9964	0.9963	0.9964	0.9963	0.9974	0.9970
20	0.9929	0.9928	0.9928	0.9928	1.0011	0.9934
21	0.9921	0.9921	0.9921	0.9921	1.0004	0.9927
22	0.9915	1.0000	0.9915	1.0000	0.9998	0.992
23	0.9798	0.9792	0.9795	0.9792	0.9794	0.9832
24	0.9731	0.9725	0.9728	0.9725	0.9728	0.9765
25	0.9698	0.9692	0.9695	0.9692	0.9694	0.9732
26	0.9982	0.9475	1.0000	0.9475	0.9478	0.9674
27	0.9957	0.945	0.9976	0.9450	0.9452	0.9649
28	0.9849	0.9335	0.9868	0.9335	0.9338	0.9537
29	0.9771	0.9253	0.979	0.9253	0.9256	0.9456
30	0.9738	0.9218	0.9756	0.9218	0.922	0.9421
31	0.9698	0.9176	0.9717	0.9176	0.9179	0.9381
32	0.969	0.9167	0.9709	0.9167	0.9170	0.9372
33	0.9687	0.9164	0.9706	0.9164	0.9167	0.9369

Table 4 shows the results of load flow calculations with D-STATCOM consideration for compensation of Fixed Voltage in selected nodes and Fixed Compensation at selected nodes as per the %RUVMN. This table shows that D-STATCOM improves the voltage both nearby downstream nodes and nearby upstream nodes, especially the nodes located between D-STATCOM and the source. For fixed voltage compensation the nodes 6, 22,26 are selected as per high, low and medium values of %RUVMN. D-STATCOM installation in node 6, causes the voltage of node 6(with RUVMN value of 60.60%) to regulate 1p.u and additionally it can improve the upstream nodes (6-18) and (26-33). D-STATCOM installation in node 26 (with RUVMN value of 27.27%), causes the voltage of node 26 to 1p.u and additionally it can improve the downstream nodes (6-9) and upstream nodes (26-33).When DSTATCOM is placed at node 26(with RUVMN value of 0%) all the nodes are remained under voltage problem. It is observed from Table 4 that when D-STATCOM installations at node 6, under voltage problem in all nodes are mitigated which is shown in fig.7. Similarly for fixed compensation, the nodes 10, 22, 26 are selected as per %RUVMN values, when DSTATCOM is placed at node 10(with RUVMN value (48.47%) 5 nodes are remained under voltage problem out of 21 nodes. Similarly DSTATCOM is placed at node22and 26 for comparison purpose as shown in table 4 .

From table 5 the real power loss and requirement of reactive power is reduced by placing D-STATCOM at 10, 22 and 26 nodes.

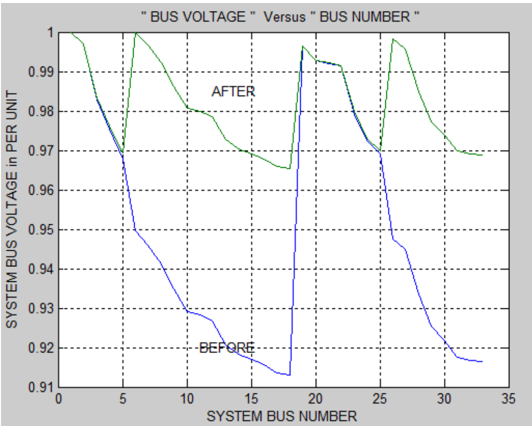

Fig. 7. Voltage vs Bus Number graph when
Fixed Voltage D-STATCOM placed at node 6

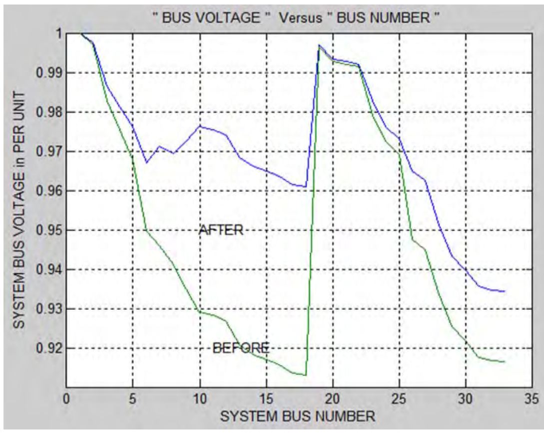

Fig.. 8. Voltage vs Bus Number graph when
Fixed Compensation D-STATCOM placed at node 10

Table 5. Losses Before and After Compensation using fixed compensation D-STATCOM

	D-STATCOM PLACED AT NODE 10		D-STATCOM PLACED AT NODE 22		D-STATCOM PLACED AT NODE 26	
	Before Compensation	After Compensation	Before Compensation	After Compensation	Before Compensation	After Compensation
Real Power Losses(KW)	203.696	114.7803	203.696	115.1588	203.696	117.1588
Reactive Power Losses(KVAR)	135.2166	77.1520	135.2166	78.8606	135.2166	76.8606

6.2 *IEEE 69 bus test system*

The line data and load data [Baran et al.(1989a)] of the 12.66kv, 69-bus, 8- lateral radial distribution system are considered. the results of load flow solution before DSTATCOM installation are presented in table 7. It is assumed that the upper and lower limits of the voltage magnitude are 1.05 p.u and 0.95 p.u., respectively. It can be seen that 9 out of 69 nodes of distribution system (13.04%) have under voltage problem. The under voltage nodes are between nodes 57-65.

Table 6 and table 7 shows the % RUVMN values for fixed compensation and fixed voltage compensation of D-STATCOM.

Table 6. RUVMN for Fixed Voltage D-STATCOM in 69-Bus distribution system

NodeNo	**RUVMN (%)**	**NodeNo**	**RUVMN (%)**	**Node No**	**RUVMN (%)**	**Node No**	**RUVMN (%)**
1	0	19	0	37	0	55	5.7971
2	0	20	0	38	0	56	10.1449
3	0	21	0	39	0	57	11.5942
4	0	22	0	40	0	58	11.5942
5	0	23	0	41	0	59	10.1449
6	1.4493	24	0	42	0	60	8.6957
7	1.4493	25	0	43	0	61	7.2464
8	2.8986	26	0	44	0	62	5.7971
9	2.8986	27	0	45	0	63	4.3478
10	0	28	0	46	0	64	2.8986
11	0	29	0	47	0	65	1.4493
12	0	30	0	48	0	66	0
13	0	31	0	49	0	67	0
14	0	32	0	50	0	68	0
15	0	33	0	51	0	69	0
16	0	34	0	52	0		
17	0	35	0	53	4.3478		
18	0	36	0	54	4.3478		

Table 7. RUVMN for Fixed Compensation D-STATCOM in 69-Bus distribution system

Node No	**RUVMN (%)**	**Node No**	**RUVMN (%)**	**Node No**	**RUVMN (%)**	**Node No**	**RUVMN (%)**
1	0	19	0	37	0	55	1.4493
2	0	20	0	38	0	56	1.4493
3	0	21	0	39	0	57	1.4493
4	0	22	0	40	0	58	2.8986
5	0	23	0	41	0	59	4.3478
6	0	24	0	42	0	60	4.3478
7	0	25	0	43	0	61	4.3478
8	0	26	0	44	0	62	4.3478
9	0	27	0	45	0	63	4.3478
10	0	28	0	46	0	64	2.8986
11	0	29	0	47	0	65	4.3478
12	0	30	0	48	0	66	0
13	0	31	0	49	0	67	0
14	0	32	0	50	0	68	0
15	0	33	0	51	0	69	0
16	0	34	0	52	0		
17	0	35	0	53	0		
18	0	36	0	54	0		

From table 8, When D-STATCOM placed at node 57 due its high RUVMN% value of 11.5972 in fixed voltage there are no under voltage mitigated nodes. The voltages before compensation and after compensation are shown in Table 8 and the graph for before and after voltages vs Bus number are represented in Fig. 9 when D-STATCOM placed at node 57.

Table 8. Voltages Before and After Compensation when Fixed Voltage DSTATCOM placed at 57th node

Node No	Before Compensation V(P.U)	After Compensation V(P.U)	Node No	Before Compensation V(P.U)	After Compensation V(P.U)	Node No	Before Compensation V(P.U)	After Compensation V(P.U)
1	1.0000	1.0000	24	0.9566	0.9575	47	0.9998	0.9998
2	1.0000	1.0000	25	0.9564	0.9574	48	0.9985	0.9985
3	0.9999	0.9999	26	0.9563	0.9573	49	0.9947	0.9947
4	0.9998	0.9998	27	0.9563	0.9573	50	0.9942	0.9942
5	0.9990	0.9991	28	0.9999	0.9999	51	0.9785	0.9794
6	0.9901	0.9905	29	0.9999	0.9999	52	0.9785	0.9794
7	0.9808	0.9816	30	0.9997	0.9997	53	0.9745	0.9757
8	0.9785	0.9794	31	0.9997	0.9997	54	0.9712	0.9725
9	0.9774	0.9784	32	0.9996	0.9996	55	0.9665	0.9682
10	0.9724	0.9734	33	0.9993	0.9994	56	0.9620	0.9639
11	0.9713	0.9723	34	0.9990	0.9990	57	0.9388	1.0000
12	0.9681	0.9691	35	0.9989	0.9989	58	0.9273	0.9893
13	0.9652	0.9662	36	0.9999	0.9999	59	0.9229	0.9851
14	0.9623	0.9633	37	0.9997	0.9997	60	0.9177	0.9731
15	0.9595	0.9604	38	0.9996	0.9996	61	0.9100	0.9727
16	0.9589	0.9599	39	0.9995	0.9995	62	0.9097	0.9723
17	0.9580	0.9590	40	0.9995	0.9995	63	0.9092	0.9723
18	0.9580	0.9590	41	0.9988	0.9988	64	0.9070	0.9702
19	0.9576	0.9586	42	0.9986	0.9986	65	0.9059	0.9691
20	0.9573	0.9583	43	0.9985	0.9985	66	0.9712	0.9722
21	0.9568	0.9578	44	0.9985	0.9985	67	0.9712	0.9722
22	0.9568	0.9578	45	0.9984	0.9984	68	0.9678	0.9688
23	0.9567	0.9577	46	0.9984	0.9984	69	0.9678	0.9688

Table 9 shows the values of voltages before and after placement of fixed compensation D-STATCOM. Here the D-STATCOM is placed at node 61 due to its high %RUVMN value of 4.3478% which is shown in table 6 and the graph was represented for before and after D-STATCOM placement which is shown in fig.10

Table 9. Voltages Before and After Compensation when Fixed Compensation DSTATCOM placed at 61th node

Node No.	Before Compensation V (P.U)	After Compensation V (P.U)	Node No.	Before Compensation V (P.U)	After Compensation V (P.U)	Node No.	Before Compensation V (P.U)	After Compensation V (P.U)
1	1.0000	1.0000	24	0.9566	0.9632	47	0.9998	0.9999
2	1.0000	1.0000	25	0.9564	0.9630	48	0.9985	0.9986
3	0.9999	1.0000	26	0.9563	0.9630	49	0.9947	0.9948
4	0.9998	0.9999	27	0.9563	0.9629	50	0.9942	0.9942
5	0.999	0.9995	28	0.9999	1.0000	51	0.9785	0.9846
6	0.9901	0.9930	29	0.9999	0.9999	52	0.9785	0.9846
7	0.9808	0.9863	30	0.9997	0.9998	53	0.9745	0.9823
8	0.9785	0.9847	31	0.9997	0.9997	54	0.9712	0.9804
9	0.9774	0.9839	32	0.9996	0.9996	55	0.9665	0.9778
10	0.9724	0.9789	33	0.9993	0.9994	56	0.9620	0.9754
11	0.9713	0.9778	34	0.999	0.9990	57	0.9388	0.9603
12	0.9681	0.9747	35	0.9989	0.9990	58	0.9273	0.9495
13	0.9652	0.9718	36	0.9999	0.9999	59	0.9229	0.9453
14	0.9623	0.9689	37	0.9997	0.9998	60	0.9177	0.9404
15	0.9595	0.9661	38	0.9996	0.9996	61	0.9100	0.9331
16	0.9589	0.9655	39	0.9995	0.9996	62	0.9097	0.9328
17	0.958	0.9647	40	0.9995	0.9996	63	0.9092	0.9325
18	0.958	0.9647	41	0.9988	0.9989	64	0.9070	0.9306
19	0.9576	0.9642	42	0.9986	0.9986	65	0.9059	0.9301
20	0.9573	0.9639	43	0.9985	0.9985	66	0.9712	0.9778
21	0.9568	0.9634	44	0.9985	0.9985	67	0.9712	0.9778
22	0.9568	0.9634	45	0.9984	0.9984	68	0.9678	0.9744
23	0.9567	0.9633	46	0.9984	0.9984	69	0.9678	0.9744

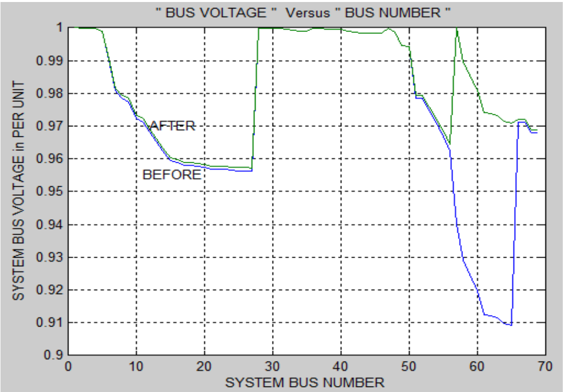

Fig 9. Voltage vs Bus Number graph when fixed Voltage D-STATCOM placed at node 57

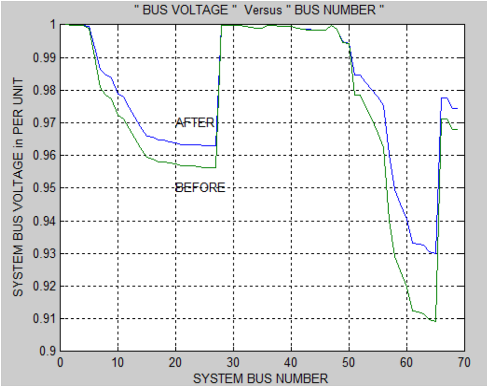

Fig 10. Voltage vs Bus Number graph when fixed Compensation D-STATCOM placed at node 61

Table 10. Losses Before and After Compensation using Fixed Compensation D-STATCOM

	D-STATCOM PLACED AT NODE 60		D-STATCOM PLACED AT NODE 55		D-STATCOM PLACED AT NODE 6	
	Before Compensation	After Compensation	Before Compensation	After Compensation	Before Compensation	After Compensation
Real Power Losses(KW)	225.0372	110.2812	225.0372	163.4357	225.0372	197.9492
Reactive Power Losses(KVAR)	102.1806	51.1066	102.1806	70.0088	102.1806	87.3069

7. Conclusion

In this paper, distribution load flow analysis was done by using forward sweep through ladder network technique. The mathematical modeling of D-STATCOM was derived and optimal placement of D-STATCOM in a distribution network is identified. This paper is carried out with both fixed compensation and fixed voltage compensation D-STATCOM and comparison had made between them. This proposed model for D-STATCOM is applied to load flow calculations in IEEE 33 and 69 bus test systems. Moreover, the optimal placements of D-STATCOM for under voltage problem mitigation approach in the test systems are derived by using RUVMN. The real power losses are also reduced in both the test systems for fixed compensation. As per results, the compensation by operating the D-STATCOM in fixed voltage mode is effective for improving the voltage profile.

8. References

[1] S. Ghosh and D. Das, Method for load-flow solution of radial distribution Networks, IEEE Proceedings on Generation, Transmission & Distribution, Vol.146, No. 6, pp. 641-648, 1999.

[2] Baran, M E and Wu F F, Optimal sizing of capacitors placed on a radial distribution system, IEEE Trans. Vol PWRD-2 (1989) 735-743.

[3] Haque, M.H., 1996, Efficient load flow method for distribution Systems with radial or meshed configuration, IEE Proc.-ener. Transm. Distrib.,143(1):33-38.[doi:10.1049/ip-gtd:19960045].

[4] Shirmohammadi D, Hong HW, Semlyen A, Luo GX. 1988, compensation based power flow method for Weakly meshed distribution networks, IEEE Trans. On Power Syst.3(2): 753-762.

[5] M. M. A. Salama, J. Liu and R. R. Mansour, An efficient power flow algorithm for distribution systems with polynomial load, International Journal of Electrical Engineering Education, Vol. 39, No. 4, pp. 372-386,2002.

[6] B. S. Chen and Y. Y. Hsu, A minimal harmonic controller for a STATCOM, IEEE Transactions on Industrial Electronics Vol. 55, No. 2, pp. 655-664, 2008.

[7] Yuan-Kang Wu,Ching-Yin Lee, Le-Chang Liu, and Shao-Hong Tsai 2010 Study of Reconfiguration for the Distribution System With Distributed Generators, IEEE Trans.on Power Delivery, VOL. 25(3) :1678-1684

[8] Baran, M.E., Wu, F.F., 1989a. Optimal capacitor placement on radial distribution systems, IEEE Trans. on Power Delivery, 4(1):725-732.[doi:10.1109/61.19265].

[9] Sensarma P.S., Padiyar K.R., Ramanarayan.,2001. Analysis and Performance Evaluation of a Distribution STATCOM for compensating Voltage Fluctuations, IEEE Trans.on Power Delivery, 16(2):259-264.

[10] M. Hosseini, S. H. Ali and F. H. Mahmud, Modeling of D-STATCOM in distribution systems load flow, Journal of Zhejiang University Science, Vol.8,No.10, pp.1532-1542, 2007, www.springerlink.com.