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Optimal Placement of Dstatcom 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 (DSTATCOM) 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).

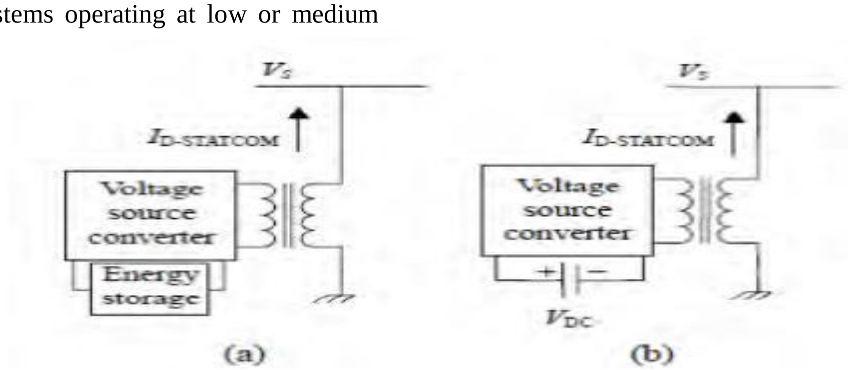

Fig. 1. A typical D-STATCOM model (a) Active and reactive power exchange (b) Only reactive power exchange

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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

$$S_i = P_i + jQ_i \tag{1}$$

Where i□ 1, 2, ... *N*

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

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

Where

Vik and Iik are the bus voltages and equivalent current injection of bus i at kth iteration respectively.

2.1 ***BIBC matrix development***

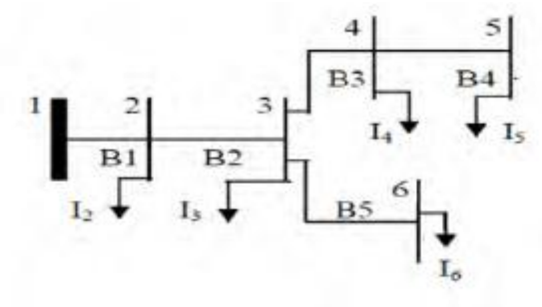

Fig. 2. Simple distribution system

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

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

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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

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

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

3. Steady-State Modeling of D-STATCOM
Consider two bus system which is shown in Fig. 3

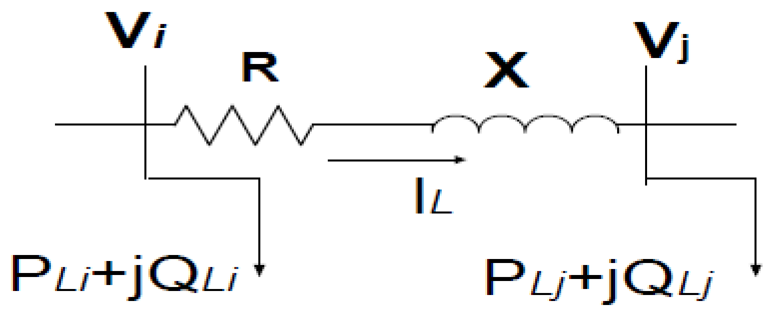

Fig. 3. single line diagram of two buses of a distribution system

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

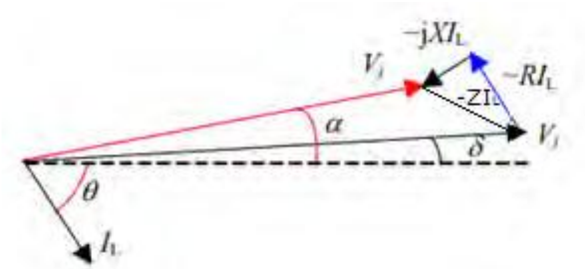

Fig. 4. Phasor diagram of voltages and current of the system shown in Fig. 3
From this phasor diagram (Fig. 4), it is drawn that,

$$Vj\angle\alpha = Vi\angle\delta - ZI_{L}\angle\theta \quad (9)$$

Where ∠ and ∠ are the voltage of buses *j* and *i* before compensation respectively,
Z=*R*+ *j X* is the impedance between buses *i* and *j*,
∠ is the current flow in line.
Voltage ∠ and current ∠ 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.

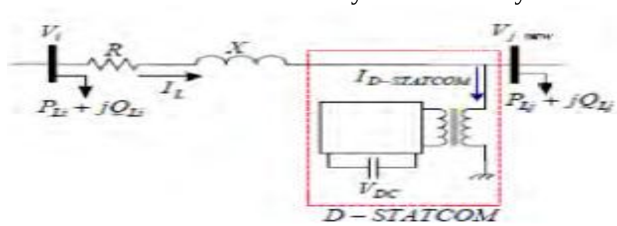

Fig. 5. Single line diagram of two buses of a distribution systems after placement of D-STATCOM

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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 *Vj* to *Vj new* when D-STATCOM is placed.

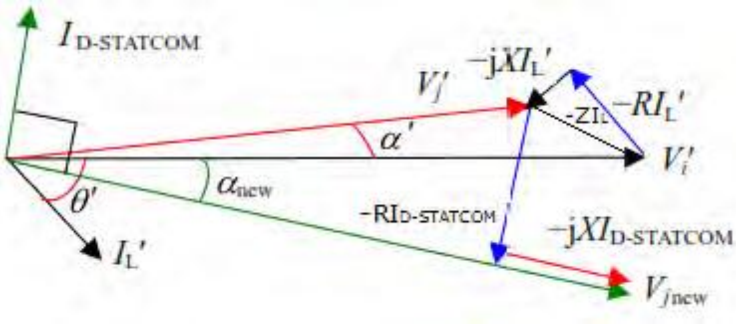

Fig. 6. Phasor diagram of voltages and current of the system shown in Fig. 5
From the phasor diagram (fig.6),

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

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

V_{jnew}□α_{new} is the voltage of bus *j* after compensation by DSTATCOM. $V'i$□δ' is the voltage of bus *i* after compensation. The value of I'_L□θ' is obtained from load flow calculations.

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

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

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

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

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

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

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

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

$$b\cos x_2 = a_1 - c_1 x_1 \sin x_2 - c_2 x_1 \cos x_2 \quad (15)$$

$$b\sin x_2 = a_2 - c_2 x_1 \sin x_2 + c_1 x_1 \cos x_2 \quad (16)$$

where
1, 2, 1 2 are constants
b is the magnitude of compensated voltage (1 p.u.) and
1, 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

$$(K_1^2 + K_2^2)x^2 + (2k_1bc_1)x + (b^2c_1^2 - k_2^2) = 0 \quad (20)$$

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

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

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

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

$$\mathbf{V}_{j\ new} = V_{j\ new}\ \angle\alpha_{new} \tag{22}$$

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

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.eVjnew) is compensated to the specific value of 1 p.u and after that, the phase angle of voltage in node j(i.eαnew),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

Bb = No.of buses which are out of constraint limit before compensation

Bc = No.of buses which are out of constraint limit remained after compensation)

Bt = Total no. of buses

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 DSTATCOM 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-

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STATCOM in fixed voltage mode is effective for improving the voltage profile.

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