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VOLTAGE STABILITY ANALYSIS FOR RADIAL DISTRIBUTION NETWORKS WITH D-STATCOM DEVICE

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Abstract: In this paper, the analysis of the voltage stability index for the most sensitive bus to the voltage collapse in the radial distribution networks is done. The performance of the index is tested on different conditions for different substation voltage levels. This paper presents about Distribution STATCOM (D-STATCOM) in load flow calculations for the steady state voltage compensation. An accurate model for D-STATCOM is used in load flow calculations. The rating of this device, direction of required reactive power injection for voltage compensation in the desired value (1 p.u.) is discussed analytically and mathematically by the phasor diagram method. Furthermore, an efficient method for node and line identification used in load flow calculations. Results are obtained using MATLAB package.

Keywords:D-STATCOM; stability voltage; radial distribution network.

1. INTRODUCTION

Distribution Load Flow Analysis module calculates the bus voltages, branch power factors, currents, and power flows throughout the system. In a three phase ac power system active and reactive power flows from the generating station to the load through different buses and branches. The flow of active and reactive power is called power flow. With the increased loading and exploitation of the existing power structure, the probability of occurrence of voltage collapse are greater than before and the identification of nodes which prone to the voltage fluctuations attracts more attention forthetransmission and as well as the distribution systems.Distribution STATCOM (D-STATCOM) is a shunt connected voltage source converter which has been utilized to compensate power quality problems such as unbalanced load, voltage sag, voltage fluctuation and voltage unbalance. D-STATCOM can inject both active and reactive power to the system for compensation of sensitive loads, and active power injection to the system.

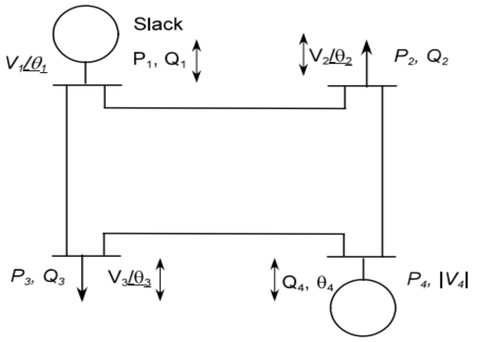

Figure-1: General radial distribution system

2. LOAD FLOW ANALYSIS

- Gauss-Seidel method
- Newton-Raphson method

2.1 Gauss-Seidel method

The Gauss-Seidel method is based upon substituting nodal equations into each other. The iteration process can be visualized for Equations: Although not the best load-flow method, Gauss-Seidel is easy to understand and most widely used technique.

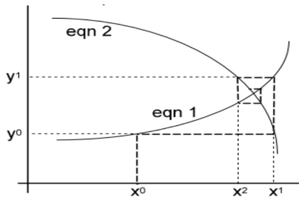

Figure-2: Load flow upon Gauss-Seidel method

2.2 Newton-Raphson method

The Newton-Raphson method is the most efficient load-flow algorithm. The basic Newton-Raphson algorithm is based on the formal application of a algorithm for the solution of a set of simultaneous non-linear equations of the form:

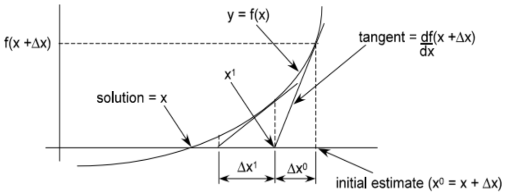

Figure-3: Load flow upon Newton-Raphson method

3. VOLTAGE STABILITY INDEX

Basing on the bus data and load data the voltage indices [18], [19], [20] of the respective test buses are taken and the critical voltages are marked. The 33-bus and 69-bus balanced radial distribution systems are chosen to demonstrate the effectiveness. Line and load data of the test systems are taken from, IEEE 33-bus and 69-bus distribution systems. The index value of each node is provided for the base load of the test systems.

3.1 Features of RDN

1. Uncertainties and Imperfection of distribution network parameters.

2. R/X ratio is high

3. Large number of nodes and branches.

4. Dynamic change for imposed loads.

3.2 Voltage Stability Index based on voltage magnitudes

For a distribution line model, given in Figure.2, the quadratic Equation which is mostly used for the calculation of the line sending end voltages in load flow analysis can be written in general form as

$$V_r^4+2V_r^2(PR+QX)-V_s^2V_r^2+(P^2+Q^2)|Z|^2=0 \qquad (1)$$

and from this Equation, line receiving end active and reactive power can be written

$$P=[-Cos(\theta_z)V_r^2\pm\{Cos^2(\theta_z)V_r^4-V_r^4-|Z|^2Q^2-2V_r^2QX+V_s^2V_r^2/|Z|\}^{1/2} \qquad (2)$$

$$Q=[-Sin(\theta_z)V_r^2\pm\{Sin^2(\theta_z)V_r^4-V_r^4-|Z|^2P^2-2V_r^2PR+V_s^2V_r^2/|Z|\}^{1/2} \qquad (3)$$

$$Cos^2(\theta_z)V_r^4-V_r^4-|Z|^2Q^2-2V_r^2QX+V_s^2V_r^2\geq0 \qquad (4)$$

$$Sin^2(\theta_z)V_r^4-V_r^4-|Z|^2P^2-2V_r^2PR+V_s^2V_r^2\geq0 \qquad (5)$$

Summing, two Equations. (4) and (5), we get

$$2V_s^2V_r^2-V_r^4-2V_r^2(PR+QX)-|Z|^2(P^2+Q^2)\geq0 \qquad (6)$$

$$VSI_1=2V_s^2V_r^2-V_r^4-2V_r^2(PR+QX)-|Z|^2(P^2+Q^2) \qquad (7)$$

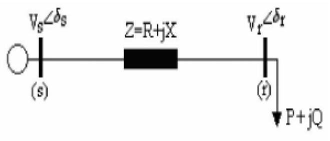

Figure-4: One line diagram of two bus distribution system

3.3 Voltage stability index based on identifying node which is sensitive

From Figure.5, the following Equation can be written:

$$I(j)=\frac{V(i)-V(i+1)}{r(j)+jx(j)} \qquad (8)$$

Where

j = branch number

i = sending end node

(i+1) = receiving end node

I(j) = current of branch j

V(i) = voltage of node i

V(i+1) = voltage of node i+1

P(i+1) = total real power load fed through node i+1

Q(i+1) = total reactive power load fed through node i+1

From Equation(8),

$$|V(i+1)|^4-b(j)|V(i+1)|^2+c(j)=0 \qquad (9)$$

Let,

$$b(j)=\{|V(i)|^2-2P(i+1)r(j)-2Q(i+1)x(j)\} \qquad (10)$$

$$c(j)=\{|P^2(i+1)|+Q^2(i+1)\}\{r^2(j)+x^2(j)\} \qquad (11)$$

The solution of Equation (9) is unique. That is

$$|V(i+1)|=0.707[b(j)+\{b^2(j)-4c(j)\}^{\frac{1}{2}}]^{\frac{1}{2}} \qquad (12)$$

$$b^2(j)-4c(j)\geq0 \qquad (13)$$

From Equations (10), (11) and (13) we get

$$\{|V(i)|^4 - 2P(i+1)r(j) - 2Q(i+1)x(j)\}^2 - 4\{P^2(i+1)+Q^2(i+1)\}\{r^2(j)+x^2(j)\} \geq 0 \qquad (14)$$

By simplification the voltage stability index is as follows

$$SI(i+1)=\{|V(i)|^4 - 4.0\{P(i+1)x(j)-Q(i+1)r(j)\}^2 - 4.0\{P(i+1)r(j)+Q(i+1)x(j)\}|V(i)|^2 \qquad (15)$$

Where

SI (i+1) = voltage stability index of node i+1.

4. ANALYSIS OF D-STATCOM

D-STATCOM is a shunt device that injects or absorbs both active and reactive current.

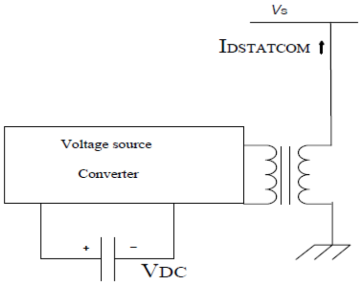

Figure-5: Schematic diagram for D-STATCOM for voltage stability

In this model, D-STATCOM is capable of injecting active power in addition to reactive power. Since energy storage has a capacity limit, it cannot 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 (Figure.6-b.).

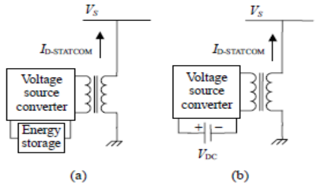

Figure-6:A typical model of D-STATCOM. (a) Active and reactive power exchange (b) Only reactive power exchange

4.1 Advantages and Applications

D-STATCOM is utilized for the improvement of another aspect of power quality, i.e. voltage compensation in long term. Since this device is utilized in steady-state condition for long term, because of limited capacity of energy storage system, it cannot inject active power to the system for long term. Therefore, a suitable model for D-STATCOM has been proposed in load flow program, which is applicable in large distribution systems. Also, the rating and direction of reactive power which must be exchanged by D-STATCOM for voltage compensation in the desired value (1 p.u.) are derived and discussed analytically and mathematically by using phasor diagram method. Then, the effects of DSTATCOM on voltage improvement at other nodes are considered and the best location of D-STATCOM for under voltage problem mitigation in the distribution network is determined. Standard distribution systems consisting [13], [14] of 32 nodes and 68 nodes are considered and the D-STATCOM model is applied to load flow. Increased power transfer capability

- Additional flexibility in grid operations
- Improved grid voltage stability
- Improved grid voltage control
- Improved power factor
- Eliminated flicker
- Harmonic filtering
- Voltage balancing
- Power factor correction
- Furnace / mill process productivity improvement
- Grid voltage support
- Power quality (flicker mitigation, voltage balancing)

4.2 Steady-State modelling of D-STATCOM

The single line diagram of two buses of a distribution system and its phasor diagram are shown in Figure.8 and Figure.9, respectively. Generally, voltage of buses in the system is less than 1 p.u. and it is desired to compensate voltage of interested bus (Vj) to 1 p.u.by using D-STATCOM.

In Figure.8, the relationship between voltage and current can be written as:

$$V_j\angle\alpha = V_i\angle\delta - ZI_L\angle\theta \qquad (16)$$

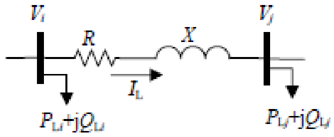

Figure-7:Single line diagram of two buses of a distribution system. Subscript 'L' in P_L and Q_L refers to the load connected to each bus

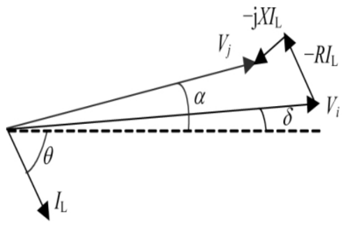

Figure-8: Phasor diagram of voltages and current of the system shown in Figure.7

Where,

$V_j\angle\alpha$ and $V_i\angle\delta$ are the voltage of buses j and i before compensation respectively, Z=R + jX is the impedance between buses i and j, $I_L\angle\theta$ is the current flow in line. Voltage $V_i\angle\delta$ and current $I_L\angle\theta$ are derived from the load flow calculations.

D-STATCOM is used for voltage regulation [15], [16] in the steady-state condition and can inject only reactive power to the system. Consequently, $I_{D-STATCOM}$ must keep in quadrature with voltage of the system. By installing D-STATCOM in distribution system, all nodes voltage, especially the neighbouring nodes of D-STATCOM location, and branches current of the network, change in the steady-state condition. The schematic diagram of buses i and j of the distribution systems, when D-STATCOM is installed for voltage regulation in bus j.

Where,

$I_{D-STATCOM}\angle$ (π / 2 +α_{new}) is the injected current by D-STATCOM,

$V_{jnew}\angle\alpha_{new}$ is the voltage of bus j after compensation by D-STATCOM,

$V_i'\angle\delta'$ is the voltage of bus i after D-STATCOM installation,

$I_L'\angle\theta'$ is the current flow in the line after D-STATCOM installation.

Voltage $V_i'\angle\delta'$ and the current flow in the line after D-STATCOM installation.

Voltage $V_i'\angle\delta'$ and current $I_L'\angle\theta'$ are derived from the load flow calculations.

It can be seen from Figure.10. and Figure.11 that:

$$\angle I_{D-STATCOM} = \frac{\pi}{2} + \alpha_{new}, \alpha_{new} < 0, \qquad (17)$$

$$V_{jnew}\angle\alpha_{new} =$$
$$V_i'\angle\delta' - (R + jX)I_L'\angle\theta' - (R + jX)I_{D-STATCOM}\angle\left(\alpha_{new} + \frac{\pi}{2}\right) \qquad (18)$$

Separating the real and imaginary parts of Equation (18) yields:

$$V_{jnew}\cos\alpha_{new} = \mathrm{Re}(V_i'\angle\delta') + XI_{D-STATCOM}\sin\left(\frac{\pi}{2} + \alpha_{new}\right) - \mathrm{Re}(ZI_L'\angle\theta') - RI_{D-STATCOM} \qquad (19)$$

$$V_{jnew}\sin\alpha_{new} = \mathrm{Im}(V_i'\angle\delta') - XI_{D-STATCOM}\cos\left(\frac{\pi}{2} + \alpha_{new}\right) - \mathrm{Im}(ZI_L'\angle\theta') - RI_{D-STATCOM}\sin\left(\frac{\pi}{2} + \alpha_{new}\right) \qquad (20)$$

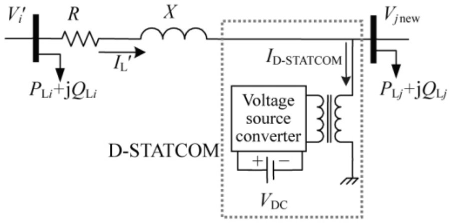

Figure-9:Single line diagram of two buses of a distribution system with D-STATCOM consideration.

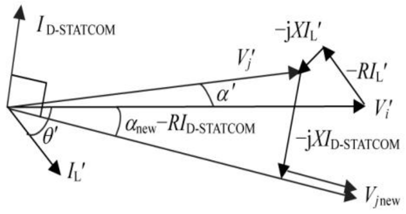

Figure-10: Phasor diagram of voltages and currents of the system shown in Figure.8

Using the notations below,

$a_1 = \mathrm{Re}(V_i'\angle\delta') - \mathrm{Re}(ZI_L'\angle\theta')$

$a_2 = \mathrm{Im}(V_i'\angle\delta') - \mathrm{Im}(ZI_L'\angle\theta')$

$x_1 = I_{D-STATCOM}$, $x_2 = \alpha_{new}$

$c_1 = -R$, $c_2 = -X$, $b = V_{jnew}$

Equations (21) and (22) are obtained from Equations. (20) and (19) respectively:

$$b\cos x_2 = a_1 - c_1 x_1 \sin x_2 - c_2 x_1 \cos x_2 \qquad (21)$$

$b\sin x_2 = a_2 - c_2 x_1 \sin x_2 - c_1 x_1 \cos x_2$ (22)

Where

a_1, a_2, c_1 and c_2 are constants b is the magnitude of compensated voltage (e.g. 1p.u.),x_1,x_2 are variables to be determined. Rearranging the equations, (21) and (22) for $x_1$yields

$$x_1 = \frac{b\cos x_2 - a_1}{-c_2 \sin x_2 + c_2 \cos x_2} \quad (23)$$

$$x_1 = \frac{b\sin x_2 - a_2}{-c_2 \sin x_2 + c_1 \cos x_2} \quad (24)$$

By Equating Equations (23) and (24),

$$(a_1 c_2 - a_2 c_1)\sin x_2 + (-a_1 c_1 - a_2 c_2)\cos x_2 + bc_1 = 0 \quad (25)$$

Considering x =$\sin x_2$, the following equation:

$$(k_1^2 + k_2^2)x^2 + (2k_1 bc_1)x + (b^2 c_1^2 - k_2^2) = 0 \quad (26)$$

Where

$k_1 = a_1 c_2 - a_2 c_1$, $k_1 = a_1 c_1 + a_2 c_2$

Therefore

$$x = (-B \pm \sqrt{\Delta}) / (2A), \quad (27)$$

Where

$\Delta = B^2 - 4AC,$

$A = k_1^2 + k_2^2,\ B = 2k_1 bc_1,\ C = b^2 c_1^2 - k_2^2$

After identifying x, $x_2 = \alpha_{new}$(angle of corrected voltage) is defined as:

$$x_2 = \arcsin x \quad (28)$$

Thus,

$x_1 = I_{D-STATCOM}$is defined by equations (23) or (24). It can be seen in equation (27) that there are two roots for x and therefore, two values are calculated for $x_2$and x_1, but only one is acceptable. To determine the correct answer, these roots are examined under boundary conditions in the load flow results.

If b=$V_{jnew} = V_j$, then $x_1 = I_{D-STATCOM} = 0$ and $x_1 = \alpha_{new} = \alpha$

After testing these conditions on load flow results, x = (-B±$\sqrt{\Delta}$) / (2A) is selected as the correct answer for Equation (26) and then x_2 andx_1 are calculated from Equations (28) and (23) respectively.

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

$$jQ_{D-STATCOM} = V_{jnew} I^*_{D-STATCOM} \quad (29)$$

Where

$V_{jnew} = V_{jnew}\angle\alpha_{new},$

$I_{D-STATCOM} = I_{D-STATCOM}\angle(\alpha_{new} + \frac{\pi}{2}),$

and '*' denotes conjugate of complex variable.

5. Methods of compensation using D-STATCOM.

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

- Compensation with fixed voltage
- Compensation with fixed rating

6. Incorporation of D-STATCOM in load flow

Load flow is an important and basic method for analysis, operation and planning studies of any power system in a steady-state condition. By using load flow, it can be determined which variables exceed their limits, and thus efficient corrective solutions such as shunt, series and other compensation techniques must be taken to stir the state variables within an acceptable and secured operating zone. Most distribution systems are fed at one point and have a radial structure. Several methods have been developed based on the concept of doing backward/forward sweeps of radial network [17]. An efficient and simple load flow method based on backward/forward sweeps is used in this paper. However, the equation presented for calculating current flow in has additional calculation operation. Based on node and branch numbering procedure, voltage of node i can be expressed.

$$V(i) = V(i-1) - I(i)Z(i) \quad (30)$$

Where

V (i) and V (i−1) are the voltage of nodes i and i−1 respectively, The load current of node i, I_L (i), can be written as:

$$I_L(i) = \frac{P_L(i) - Q_L(i)}{V^*(i)} \quad (31)$$

Where

P_L (i) and Q_L (i) are active and reactive power of load connected to node i, respectively. The current through a branch i, i.e. I (i), equals I_L (i) plus the sum of the branch currents connected to this line:

$$I(i) = I_L(i) + \sum_{j\in\beta_i} I(j) \qquad (32)$$

Where,

β_i is the set consisting of all branches connected to node i. Thus, β_i is empty for each end node. As a result, I (i) connected to the end node i can be expressed as:

$$I(i)=I_L(i) \qquad (33)$$

7. Figures

Here we are considering IEEE 33 bus and 69 bus system for which the graphs are obtained as below. The voltage stability indices, power losses etc. can be considered and further studies can be continued.

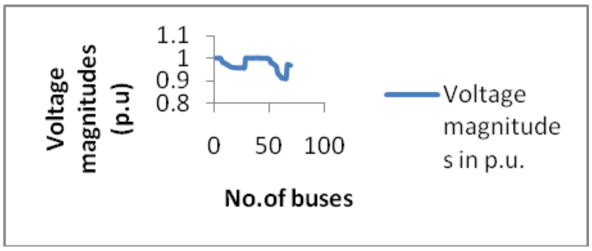

Figure-11: Voltage magnitudes without compensation

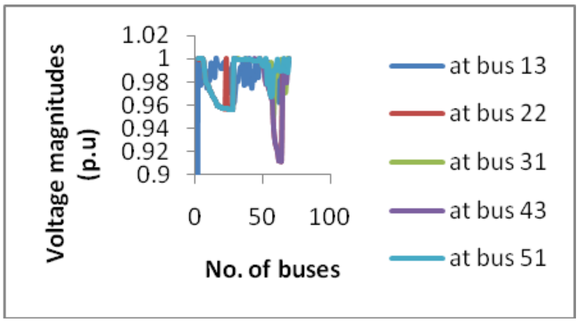

Figure-12: Voltage magnitudes with compensation

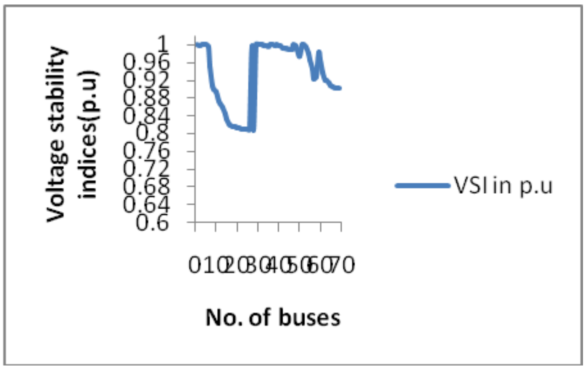

Figure-13: Voltage stability indices without compensation

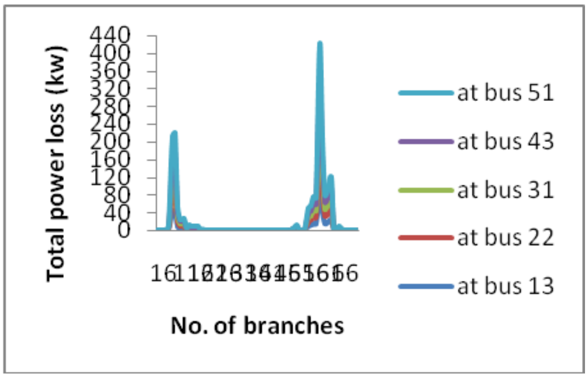

Figure-14: Total real power loss with compensation (KW)

8. CONCLUSION

A novel, fast, robust load flow algorithm applicable in electrical power distribution system analysis for various loading and phasing conditions is presented. The conformity of the results obtained for the different systems and robustness of the proposed method. Developed stability index was tested on the different conditions for different type of load of distribution networks. Results show that the proposed index is robust and can provide useful information for the most sensitive bus to the voltage collapse at any operating point of radial networks. In this work, the problems associated with determination of proper D-STATCOM location, power losses, voltage magnitudes with compensation and without compensation are considered. Therefore, D-STATCOM was applied on the 33-bus and 69-bus. While the minimum ΔV is achieved by installation of D-STATCOM, the maximum power loss happens in these nodes. According to these results, installation of D-STATCOM is suggested. This causes improving voltage profile and power loss reduction.

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