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Voltage Stability Analysis of Radial Distribution Networks for Loads of Composite Type using Shunt Capacitor at Optimal Position

[K Dasgupta, S Banerjee C K Chanda]

Abstract— ***The paper presents voltage stability analysis of radial distribution networks for composite type of loads without and with considering shunt capacitor. A new voltage stability index is proposed for identifying the node, which is most sensitive to voltage collapse. The effectiveness of the proposed method without and with considering shunt capacitor is demonstrated through an 12.66 kV radial distribution networks consisting of 33 nodes*****.**

Keywords— Voltage stability index; radial distribution system; shunt capacitor; voltage collapse; weakest node.

I. INTRODUCTION

Voltage collapse may occur in a power system due to lost in voltage stability in the system. Voltage collapse is the phenomenon of voltage instability that can appear in a transmission or distribution system operating under the heaviest loading conditions, in which the voltage decreases monotonically leading the system to be blackout. While in normal operating conditions, small loads increase causes a small voltage drop but if the entire network or a particular node is over a certain critical load level; further loads increase causes a fast decrease of the voltage which suddenly leads the system to the collapse. Therefore voltage stability analysis is important in order to identify critical nodes in a power system i.e. nodes which are closed to their voltage stability limits and thus enable certain measures to be taken by the control engineer in order to avoid any incidence of voltage collapse.

Voltage stability [1] may be explained as the ability of a power system to maintain voltage at all the nodes of the system so that with the increase of load, load power will increase and both the power and voltage are controllable. The problem of voltage stability [1] has been defined as inability of the power system to provide the reactive power [2] or non-uniform consumption of reactive power by the system itself.

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Therefore, voltage stability is a major concern in planning and assessment of security of large power systems in contingency situation, specially in developing countries because of non-uniform growth of load demand and lacuna in the reactive power management side [3]. The loads generally play a key role in voltage stability analysis and therefore the voltage.

stability is known as load stability. Literature survey shows that a major work has been done on the voltage stability analysis of transmission systems, but so far the researchers have paid very little attention on the voltage stability analysis for a radial distribution network [4-12] in power system.

A radial distribution system consists of root node, main line, lateral line, sub lateral line and minor line with some uniform and non-uniform tapings. Radial distribution system having a high resistance to reactance ratio, which causes a high power loss whereas the transmission system having a high reactance to resistance ratio. So, the conventional load flow methods like Newton Raphson and fast decoupled method cannot be effectively used for the load flow analysis of radial distribution systems.
All the 11 KV rural distribution feeders are radial in nature and longitudinal in behavior due to vastness of our country like India. The voltages at the distant end of many such radial feeders are very low which demands high voltage regulation.

In this paper, a new voltage stability index for all the nodes is proposed for radial distribution networks considering composite types of loads without and with considering shunt capacitors. It is shown that the node, at which the value of voltage stability index is maximum, is more sensitive to voltage collapse.

II. BASIC THEORY

A distribution networks consists of N number of nodes. Normally, a number of branches are series connected to form a radial feeder in low voltage distribution system. Let any branch line is b_{jj} where i and (i+1) are respectively two nodes of the branch and node i is sending end node [sending end voltage $V(i)\angle\delta(i)$] and node (i+1) is receiving end node [voltage, $V(i+1)\angle\delta(i+1)$]. Therefore, power flow direction is from node i to node (i+1). The load flow from node (i+1) is { $P(i+1)+jQ(i+1)$ }. The impedance of the branch b_{jj} is $R(i)+jX(i)$. If line shunt admittances are neglected, the current flowing through the line is given by,

$$I(i)=\frac{|V(i)|\angle\delta(i)-|V(i+1)|\angle\delta(i+1)}{R(i)+jX(i)} \tag{1}$$

The complex power is written as

$$S(i+1)=P(i+1)+jQ(i+1)=V(i+1)I^*(i)$$

or, $$I(i)=\frac{P(i+1)-jQ(i+1)}{V^*(i+1)}=\frac{P(i+1)-jQ(i+1)}{|V(i+1)|\angle-\delta(i+1)} \tag{2}$$

From (1) and (2)

$$\frac{P(i+1)-jQ(i+1)}{|V(i+1)|\angle-\delta(i+1)}=\frac{|V(i)|\angle\delta(i)-|V(i+1)|\angle\delta(i+1)}{R(i)+jX(i)} \tag{3}$$

$$\begin{aligned}&[R(i)P(i+1)+X(i)Q(i+1)]+j[X(i)P(i+1)-R(i)Q(i+1)]=\\&|V(i)||V(i+1)|[\cos(\delta(i)-\delta(i+1))+j\sin(\delta(i)-\delta(i+1))]-|V(i+1)|^2\end{aligned} \tag{4}$$

Equating real and imaginary part of (4), we get

$$\begin{aligned}&[R(i)P(i+1)+X(i)Q(i+1)]=\\&|V(i)||V(i+1)|\cos(\delta(i)-\delta(i+1))-|V(i+1)|^2\end{aligned} \tag{5}$$

and

$$\begin{aligned}&[X(i)P(i+1)-R(i)Q(i+1)]=\\&|V(i)||V(i+1)|\sin(\delta(i)-\delta(i+1))\end{aligned} \tag{6}$$

From (5) and (6), we get

$$\begin{aligned}&|V(i)||V(i+1)|\cos(\delta(i)-\delta(i+1))-|V(i+1)|^2=\\&R(i)\left[\frac{|V(i)||V(i+1)|\sin(\delta(i)-\delta(i+1))+R(i)Q(i+1)}{X(i)}\right]\\&+X(i)Q(i+1)\end{aligned}$$

$$\begin{aligned}&|V(i+1)|^2+|V(i)||V(i+1)|\left[\begin{aligned}&\left\{\frac{R(i)}{X(i)}\right\}\sin(\delta(i)-\delta(i+1))\\&-\cos(\delta(i)-\delta(i+1))\end{aligned}\right]\\&+Q(i+1)\left[\frac{R^2(i)}{X(i)}+X(i)\right]=0\end{aligned} \tag{7}$$

The equation (7) is quadratic in nature and to have real roots, the discriminate must be greater than or equal to zero.
From (7), we get

$$\begin{aligned}&|V(i)|^2\left[\left\{\frac{R(i)}{X(i)}\right\}\sin(\delta(i)-\delta(i+1))-\cos(\delta(i)-\delta(i+1))\right]^2\\&-4Q(i+1)\left[\frac{R^2(i)}{X(i)}+X(i)\right]\geq 0\end{aligned} \tag{8}$$

Generally in radial distribution system, the voltage angle is negligibly small. So, $[\delta(i)-\delta(i+1)]\cong 0$ .Hence, $\left[\left\{\frac{R(i)}{X(i)}\right\}\sin(\delta(i)-\delta(i+1))-\cos(\delta(i)-\delta(i+1))\right]^2\cong 1$. Therefore,

from (8)

$$|V(i)|^2-4Q(i+1)\left[\frac{R^2(i)}{X(i)}+X(i)\right]\geq 0$$

$$\frac{4Q(i+1)}{|V(i)|^2X(i)}\left\{R^2(i)+X^2(i)\right\}\leq 1 \tag{9}$$

Here $\frac{4Q(i+1)}{|V(i)|^2X(i)}\left\{R^2(i)+X^2(i)\right\}$ is termed as Local Voltage Stability Indicator (VSI) and to maintain stability, the condition is VSI ≤ 1. If the value of VSI exceeds unity, then the corresponding distribution line is very much unstable. So for safer operation of the system, the Local Voltage Stability Indicator (VSI) should be less than unity.

Hence

$$VSI=\frac{4Q(i+1)}{|V(i)|^2X(i)}\left\{R^2(i)+X^2(i)\right\} \tag{10}$$

III. LOAD MODELING

For the purpose of loading status of all branches of radial distribution networks, composite load modeling is considered. The real and reactive power loads of node ‘i’ is given as:

$$PL(i)=PL_0(i)\left(c_1+c_2|V(i)|+c_3|V(i)|^2\right) \tag{11}$$

$$QL(i)=QL_0(i)\left(d_1+d_2|V(i)|+d_3|V(i)|^2\right) \tag{12}$$

Here (c_1,d_1), (c_2,d_2), and (c_3,d_3) are the compositions of constant power (CP), constant current (CI) and constant impedance (CZ) loads respectively. Now, for constant power load $c_1=d_1=1$, $c_2=d_2=c_3=d_3=0$, for constant current load $c_2=d_2=1$, $c_1=d_1=c_3=d_3=0$, and for constant impedance load $c_3=d_3=1$, $c_1=d_1=c_2=d_2=0$. Here, for composite load, a composition of 40% of constant power $(c_1=d_1=0.4)$, 30% of constant current $(c_2=d_2=0.3)$ and 30% of constant impedance $(c_3=d_3=0.3)$ loads are also considered.

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IV. RESULT AND DISCUSSIONS

The effectiveness of the proposed VSI is tested on 12.66 kV radial distribution systems consisting of 33 nodes. The single line diagram of the 33-node network is shown in Fig. 1 and its data are given in Appendix.

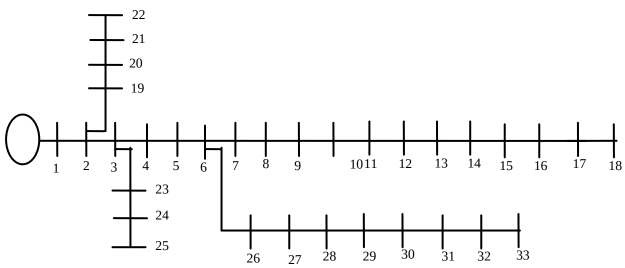

Figure 1:Single line diagram of a main feeder.

The voltage stability index is evaluated using equation (10) for composite type of load. Then the voltage stability index of all nodes of the network under nominal loading condition are shown in Fig. 2 and the investigation reveals that the value of the voltage stability index is maximum at node 6. Thus node 6 is considered to be the weakest node of the network.

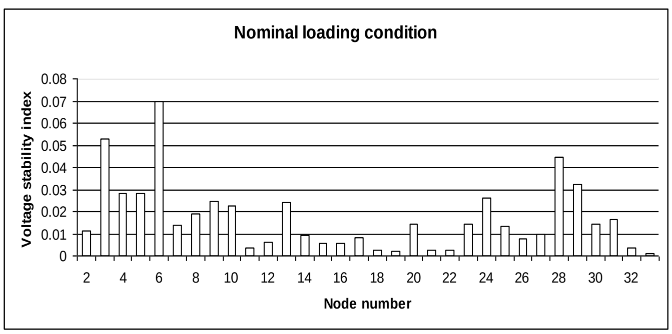

Figure 2: Voltage stability indicator of all branches of 33 node network for composite type of load under nominal loading condition.

Now, active and reactive loads of all the nodes are increased i.e., $\{PL(i) = \alpha.PL_o(i)$ and $QL(i) = \alpha.QL_o(i)$ for $i = 2,3,4.....................,NB$ and α is increased from zero to a critical value where voltage collapses.}. Then the voltage stability index of all nodes of the network under critical loading condition are shown in Fig. 3 and the investigation also reveals that the value of the voltage stability index is maximum at node 6. Thus node 6 is considered to be the weakest node of the network.

Fig. 4 shows the plot of voltage stability index Vs. load multiplier factor (α) of the weakest node (node 6) of 33-node network under critical loading condition.

Fig. 5 shows the plot of voltage magnitude of node 18 Vs. load multiplier factor (α) under critical loading condition.

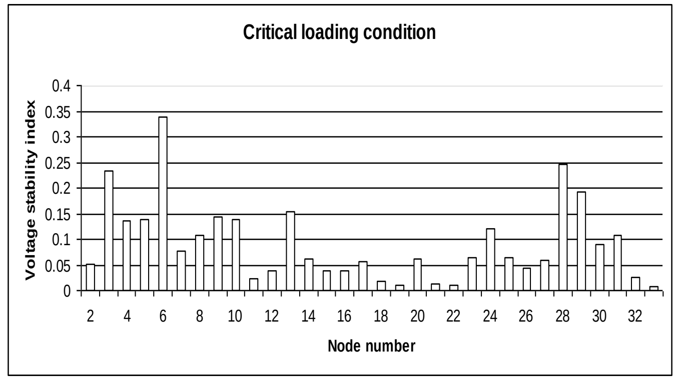

Figure 3: Voltage stability indicator of all branches of 33 node network for composite type of load under critical loading condition.

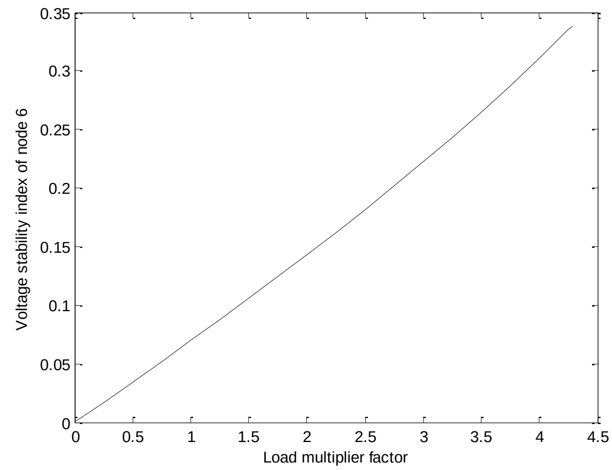

Figure 4: Voltage stability index Vs. load multiplier factor (α) of the weakest node (node 6) of 33-node network under critical loading condition without capacitor.

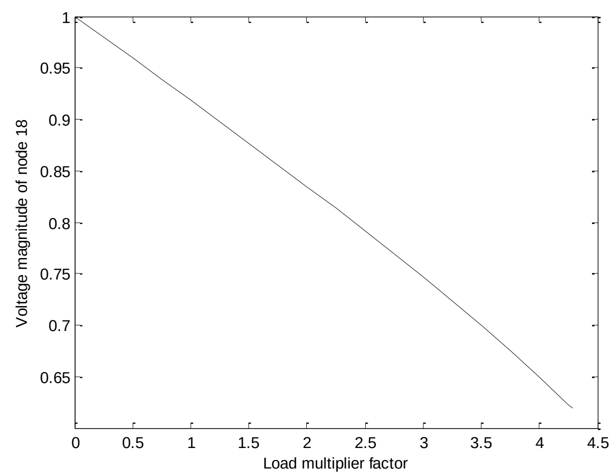

Figure 5: Voltage magnitude Vs. load multiplier factor (α) of the weakest node (node 18) of 33-node network under critical loading condition without capacitor.

Now a 400 kVAr shunt capacitor bank is inserted at node 30. Then, active and reactive loads of all the nodes are increased {i.e., $PL(i) = \alpha.PL_o(i)$ and $QL(i) = \alpha.QL_o(i)$ for $i = 2,3,4.....................,33$ and α is increased from zero to a critical value where voltage collapses.}. When the load of all nodes is successively increased, the power flow algorithm successfully converged for a load multiplier factor of up to 4.90608 (for composite load). This point is considered to be the critical loading point beyond which a small increment of load causes the voltage collapse.

Fig. 6 shows the plot of voltage stability index Vs. load multiplier factor (α) of the weakest node (node 6) with capacitor at optimal location of 33-node network for composite load under critical loading condition.

Fig. 7 shows the plot of voltage magnitude of node 18 Vs. load multiplier factor (α) with capacitor at optimal location of 33-node network for composite load under critical loading condition.

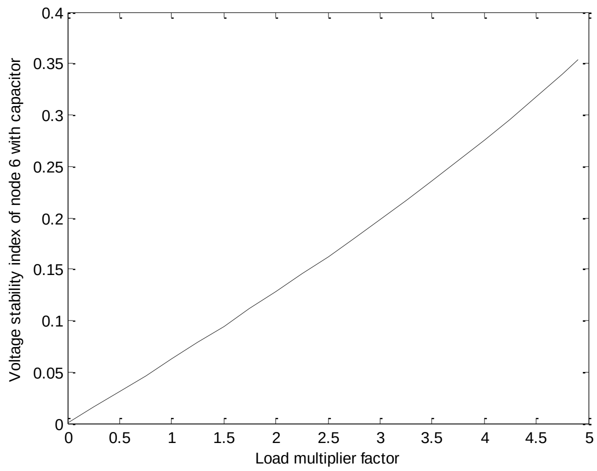

Figure 6: Voltage stability index Vs. load multiplier factor (α) of the weakest node (node 6) of 33-node network under critical loading condition with capacitor.

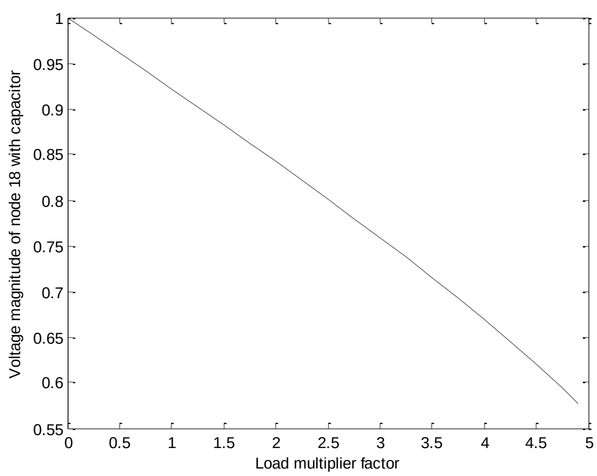

Figure 7: Voltage magnitude of node 18 Vs. load multiplier factor (α) of 33-node network under critical loading condition with capacitor.

Fig 8 shows the comparison of voltage stability index of node 6 without and with shunt capacitor under critical loading condition.

Fig 9 shows the comparison of voltage magnitude of node 18 without and with shunt capacitor under critical loading condition.

From Figs. 8 and 9, it is seen that with the insertion of shunt capacitor at node 30, load capability limit of the feeder has increased.

From Figs 8 and 9, it is also seen that the VSI and voltage magnitude has improved after inserting shunt capacitor at node 30.

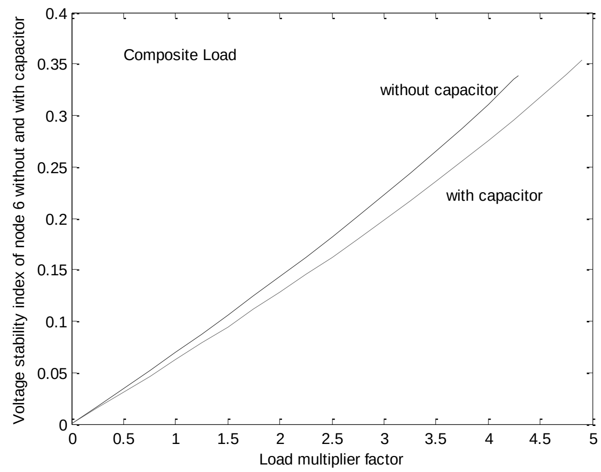

Figure 8: Comparison of voltage stability index of node 6 without and with shunt capacitor under critical loading condition.

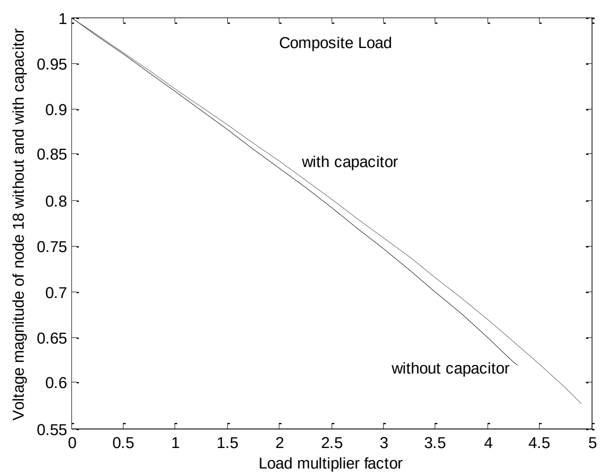

Figure 9: Comparison of voltage magnitude of node 18 without and with shunt capacitor under critical loading condition.

V. CONCLUSIONS

In this paper, voltage stability of radial distribution network without and with considering shunt capacitor has been studied. A voltage stability index of radial distribution network has been proposed. Proposed voltage stability index is capable of identifying weakest node of the feeder. Effectiveness of the proposed technique has been demonstrated through an example.

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Table I: Line data and nominal load data of 33-node radial distribution network.

Br. no. (jj)	Sending end node IS(jj)	Receiving end node IR(jj)	Branch resistance (ohm)	Branch reactance (ohm)	Nominal load at Receiving end node	
					PL_0 (kW)	QL_0 (kVAr)
1	1	2	0.0922	0.0477	100.0	60.0
2	2	3	0.4930	0.2511	90.0	40.0
3	3	4	0.3660	0.1840	120	80
4	4	5	0.3811	0.1941	60	30
5	5	6	0.8190	0.7000	60	20
6	6	7	0.1872	0.6188	200	100
7	7	8	0.7114	0.2351	200	100
8	8	9	1.0300	0.7400	60	20
9	9	10	1.0400	0.7400	60	20
10	10	11	0.1966	0.0650	45	30
11	11	12	0.3744	0.1238	60	35
12	12	13	1.4680	1.1550	60	35
13	13	14	0.5416	0.7129	120	80
14	14	15	0.5910	0.5260	60	10
15	15	16	0.7463	0.5450	60	20
16	16	17	1.2890	1.7210	60	20
17	17	18	0.7320	0.5740	90	40
18	2	19	0.1640	0.1565	90	40
19	19	20	1.5042	1.3554	90	40
20	20	21	0.4095	0.4784	90	40
21	21	22	0.7089	0.9373	90	40
22	3	23	0.4512	0.3083	90	50
23	23	24	0.8980	0.7091	420	200
24	24	25	0.8960	0.7011	420	200
25	6	26	0.2030	0.1034	60	25
26	26	27	0.2842	0.1447	60	25
27	27	28	1.0590	0.9337	60	20
28	28	29	0.8042	0.7006	120	70
29	29	30	0.5075	0.2585	200	600
30	30	31	0.9744	0.9630	150	70
31	31	32	0.3105	0.3619	210	100
32	32	33	0.3410	0.5302	60	40