Voltage Stability Enhancement In Radial Distribution Systems By Optimal Placement Of Capacitors

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Abstract

In this paper, to enhance voltage stability of distribution systems, a Network Topology based load flow results are used to calculate Voltage Stability Index (VSI). Then an algorithm for capacitor placement (CP) based on this voltage stability index is implemented to determine the optimal locations, number and size of fixed and/or switched shunt capacitors for voltage stability enhancement, in addition to improving voltage profile and reducing losses in the radial distribution system. The Capacitor Placement algorithm is tested on 15-Node and 85-Node Test Distribution Systems and the results are presented.

Test results show that the Capacitor Placement algorithm is effective in enhancing voltage stability of the Radial Distribution System. Also there is improvement of voltage profile and reduction of losses in the distribution systems. The Capacitor Placement algorithm is implemented using the MATLAB software.

Keywords - capacitor placement, network topology, radial distribution systems, voltage stability index, voltage stability.

I. INTRODUCTION

Distribution Systems which are radial in nature produce very low voltages at the load buses located far away from the sub-station. So the problem of voltage instability has become a matter of great concern to the utilities in view of its prediction, prevention and necessary corrections to ensure stable operation. In recent years, the load demand in distribution systems is sharply increasing due to economical and environmental pressures. The operating conditions are thus closer to the voltage stability boundaries. In addition, distribution networks experience frequent distinct load changes.

During peak load, even a small change in the load pattern may threaten the voltage stability (VS) of the system. The problem of voltage instability may simply be explained as the inability of the power system to supply the required reactive power or because of an excessive absorption of the reactive power by the system itself. Capacitors are commonly used to provide reactive power support in distribution systems. The amount of reactive power compensation provided is very much linked to the placement of capacitors in distribution feeders in the sense that it essentially determines the location, size, number and type of capacitors to be placed, as it reduces power and energy losses, increases the available capacity of the feeders and improves the feeder voltage profile.

The voltage stability (VS) of radial distribution system has been studied and voltage stability index have been developed in [1]. Voltage instability occurs in power systems when the system is unable to maintain an acceptable voltage profile under an increasing load demand and/or configuration changes. A method for estimating the voltage stability of a power system is given in [2]. Voltage Stability indicator L is defined which varies in the range between 0 (no-load of system) and 1 (voltage collapse). Based on the basic concept of such an indicator various models are derived which allow predicting voltage instability or the proximity of a collapse. Analytical approach to voltage collapse proximity determination for voltage stability assessment in radial networks is given in [3]. Under corresponding assumptions, a radial network with arbitrary bus loads is transformed into a two bus equivalent. A new static voltage stability margin (VSM) of a radial distribution system is proposed to faithfully determine the distance to voltage collapse in [4]. The proposed VSM varies almost linearly with system load and it requires only the complex bus voltages to evaluate. A single dynamic data structure for an evolutionary programming (EP) algorithm that handles the problems of sitting and sizing of new shunt capacitors simultaneously while considering transformer taps, existing reactive-power sources and reconfiguration options, accounting for different load levels and time durations is presented in [5]. Optimal reactive-power compensation in a radial distribution system requires the determination of the best set of locations for sitting capacitors of minimum sizes. An efficient method for simultaneous allocation of fixed and switchable capacitors in radial distribution systems is presented in [6]. Installation of capacitors in primary and secondary networks of distribution systems is one of the efficient methods for energy and peak load loss reduction. A discrete version of PSO is combined with a radial distribution power flow algorithm (RDPF) to form a hybrid PSO algorithm (HPSO) in [7]. The former is employed as a global optimizer to find the global optimal solution, while the latter is used to calculate the objective function and to verify bus voltage limits. A heuristic constructive algorithm (HCA) for optimal capacitor placement on distribution systems is presented in [8]. This is a nonlinear mixed integer optimization problem. An efficient algorithm for real-time network reconfiguration on large unbalanced distribution network is presented in [9]. A novel formulation of the network reconfiguration to achieve loss minimization and load balancing is given. By reconfiguring the network, voltage stability can be maximised for a particular set of loads in distribution systems is presented in [10].

The power flow used in this study is suggested in [11]. The special topology of a distribution network has been fully exploited to make obtaining a direct solution possible. Two developed matrices are enough to obtain the power flow solution: they are the bus-injection to branch-current matrix and the branch-current to bus-voltage matrix. The traditional Newton Raphson and Gauss implicit Z matrix algorithms, which need LU decomposition and forward/backward substitution of the Jacobian matrix or the Y admittance matrix, are not needed for this new development. Two matrices, developed based on the topological structure of distribution systems, have been used to solve the load flow problem. The BIBC matrix is responsible for the variation between the bus current injection and branch current, and the BCBV matrix is responsible for the variation between the branch current and bus voltage. The proposed solution algorithm is primarily based on these two matrices and matrix multiplication. Time-consuming procedures, such as LU (Lower Upper) factorization and forward/backward substitution of the Jacobian matrix are not needed, and the ill-conditioned problem which occurs at the Jacobian matrix does not exist in the solution procedure. The line and load data for the 15 Node Test Radial Distribution Systems are obtained from [12]. The line and load data for the 85 Node Test Radial Distribution Systems are obtained from [13].

II. CAPACITOR PLACEMENT IN DISTRIBUTION SYSTEMS

The amount of reactive compensation provided is very much linked to the placement of capacitors in distribution feeders in the sense that it essentially determines the location, size, number and type of capacitors to be placed, as it reduces power and energy losses, increases the available capacity of the feeders and improves the feeder voltage profile. Shunt capacitors can be installed in a distribution system to a required level of reactive power support. The amount of compensation to be provided is linked with the desirable objectives subject to the operational constraints. Thus optimal capacitor placement problem aims at determination of capacitor locations and their respective sizes. So the aim of the present work is to place capacitor banks at optimal locations with a view to enhance voltage stability of radial distribution systems.

The algorithm that uses the Voltage Stability Index (VSI) for optimal locations and sizing of static and/or switched shunt capacitors in radial distribution system for voltage stability enhancement is presented. This method uses Voltage Stability Index (VSI) for reactive power support at the appropriate nodes to improve VSI values towards a fixed threshold value, which is chosen based on system configuration and the operating state. This method improves voltage profile and reduces system losses in addition to enhancing voltage stability. The method is tested on 15-Node, 33-Node, 69-Node and 85-Node Radial Distribution Systems and the results are presented.

A. Problem Formulation for Capacitor Placement Algorithm

The capacitor placement algorithm determines the number, sizes, locations and types for capacitors to be placed on a distribution system in order to enhance voltage stability. The capacitor placement algorithm uses the Voltage Stability Index (VSI) for optimal locations and sizing of static and/or switched shunt capacitors in radial distribution system for voltage stability enhancement. A Sample Distribution Line for the determination of Voltage Stability Index is shown in Fig. 3.1 below.

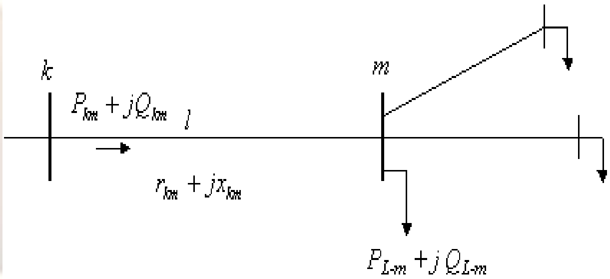

Fig. 1 Sample Distribution Line

The VSI, which varies between unity at no load and zero at voltage collapse point, for line-l or for node-m can be determined by

$$Lm = [2\frac{V_m}{V_k} \cos(\delta_{km}) - 1]^2 \qquad \dots (2.1)$$

Where,

V_m is Receiving End Voltage

V_k is Sending End Voltage

δ_k is Voltage Angle at Node k

δ_m is Voltage Angle at Node m

$\delta_{km} = (\delta_k - \delta_m)$

Linearising Eq. (3.1) and neglecting the higher order terms

$$\Delta L_m = \left(\frac{dL_m}{dV_m}\right)\Delta V_m \quad \text{... (2.2)}$$

Where

$\Delta L_m = L_m - L^t$

(L^t means threshold value for VSI)

Differentiating Eq. 3.1,

$$\frac{dL_m}{dV_m} = 8\left[\frac{V_m}{V_k^2}\right]\cos^2\delta_{km} - 4\left(\frac{\cos\delta_{km}}{V_k}\right) \quad \text{... (2.3)}$$

The net reactive power delivered by node –m can be written as

$$Q_m = -Q_{mk} = -V_m^2 B_{km} - V_m V_k G_{km}\sin\delta_{mk} + V_m V_k B_{km}\cos\delta_{mk} \quad \text{... (2.4)}$$

Where,

B_{km} is Susecptance between Nodes k and m

G_{km} is Conductance between Nodes k and m

Linearising Eq. (3.4) and neglecting the higher order terms

$$\Delta Q_m = \left(\frac{dQ_m}{dV_m}\right)\Delta V_m \quad \text{.... (2.5)}$$

Where,

$$\frac{dQ_m}{dV_m} = -2V_m B_{km} - V_k G_{km}\sin\delta_{mk} + V_k B_{km}\cos\delta_{mk} \quad \text{... (2.6)}$$

Rearranging Eq. (2.2), and substituting in Eq.(2.5), additional reactive power (ΔQ_m) is obtained as

$$\Delta Q_m = \frac{dQ_m}{dV_m}\left[\frac{dL_m}{dV_m}\right]^{-1}\Delta L_m \quad \text{... (2.7)}$$

The VSI at all nodes are computed using Eq. (3.1). If all these values are greater than a fixed threshold value L^t, it indicates that the system is away from the voltage instability point and the system does not require any reactive power compensation; else the nodes, whose VSI values are lower than the threshold value, are chosen as the candidate nodes for compensation. However, the node-m having the lowest VSI value is chosen for Capacitor Placement and the additional reactive power compensation, ΔQ_m to be provided at this node can be obtained by calculating or solving Eq. (3.7).

The calculated reactive power support is provided at node-m and the above process is continued till all the VSI values become more than the threshold value. The chosen node-m is said to be optimal as it is the most vulnerable node from voltage stability point of view and reactive support at that node ensures the system to be far away from the voltage instability point when compared to providing reactive support at all other nodes one at a time. The maximum compensation at each node is limited to the initial reactive power delivered by the respective node prior to compensation for avoiding over-dimensioning of the capacitor banks as, $Qc_m \leq Q_m^0$ where Qc_m is net reactive power compensation at node-m. Q_m^0 is reactive power delivered by node-m before compensation

The capacitor to be installed at a specific node may be either fixed or switched type, which is based on the system minimum and maximum reactive power demands, Q_{L-min} and Q_{L-max} in a defined period. They are chosen to be fixed capacitors when $\sum_{m=2}^{nn} QL-m \leq QL-min$ and switched capacitors when $QL-min \leq \sum_{m=2}^{nn} QL-m \leq QL-max$ to provide VAR support.

where Q L-m is reactive power load at node -m.

B. Algorithm for Capacitor Placement

1. Read the system data
2. A fixed threshold value, L^t for Voltage Stability Index (VSI) is chosen
3. Set net reactive power compensation (Qc_m) = 0 and flag=0 for all the nodes
4. Initial value of (Qc_m^0) = (Qc_m) for all the nodes
5. Carryout distribution power flow (Network Topology Based)
6. Compute VSI values, L_m at all nodes using Eq. (2.1)
7. Choose the node having lowest value of VSI, L^{low} as the sensitive node-m for capacitor placement whose flag =0
8. If $L^{low} \geq L^t$, for all the candidate nodes, then go to step (14)
9. If flag=1 for node m then choose the next node having lowest value of VSI, L^{low} which is less than L^t and whose flag=0 else go to step 13
10. Solve Eq. (2.7) for ▲Qm and then compute the net compensation at node m, i.e. $Q_{cm} = Q_{cm}^0 + \Delta Q_m$
11. Calculate and check the net reactive power compensation limit Q_m^o
12. If $Qc_m > Q_m^0$ then set $Qc_m = Q_m^0$ and set flag =1 for node m to avoid this node in the subsequent computations and go to step (4)
13. The optimal locations for CP are obtained. Choose the nearest available value of capacitor from the computed values of Qc_m
14. Stop.

III. CASE STUDIES, TEST RESULTS AND ANALYSIS

At first the Voltage stability Index (VSI) values of the four test Radial Distribution System are calculated for four different loading conditions i.e. (light, medium, full and overload) before compensation for finding the sensitive or candidate node for the placement of capacitor on that node. Then the requirement of VAR compensation, then type, size and number of the capacitor banks placed and then the performance of CP algorithm before and after capacitor placement is observed and tabulated below.

A. CASE-1 15- Node Test System

TABLE I. VSI Values Before Compensation for 15- Node Test System

NODE No.	Light Load	Medium Load	Full Load	Over Load
2	0.9603	0.9361	0.9197	0.9115
3	0.9803	0.9680	0.9596	0.9553
4	0.9942	0.9906	0.9880	0.9867
5	0.9986	0.9976	0.9970	0.9967
6	0.9907	0.9848	0.9806	0.9785
7	0.9972	0.9955	0.9943	0.9937
8	0.9859	0.9771	0.9710	0.9679
9	0.9989	0.9983	0.9978	0.9976
10	0.9962	0.9938	0.9921	0.9913
11	0.9901	0.9839	0.9796	0.9774
12	0.9939	0.9901	0.9874	0.9860
13	0.9981	0.9968	0.9959	0.9955
14	1.0024	1.0039	1.0049	1.0055
15	0.9964	0.9941	0.9925	0.9917

It can be observed that only at node-2, VSI value is less than threshold value (L^t) and all other nodes, VSI values are above threshold value (L^t). Hence node-2 is selected as Candidate node for Compensation.

TABLE II. Reactive Power Delivered before Compensation (Q_m^o) and Requirement of VAR Compensation at Node-2 for 15-Node Test System

Load Level	Reactive Power Delivered Before Compensation (Q_m^o) for Node-2 (KVAR)	Requirement of VAR Compensation at Node-2 (KVAR)
Light Load	625	----
Medium Load	1000	1050
Full Load	1250	1200
Over Load	1375	1350

It can be observed here for the light loading condition at node-2 does not require any compensation, as the VSI value is more than the threshold limit (L^t). However for medium, full, and over loading conditions VAR compensation is required at node-2, as the VSI values are less than the threshold limit (L^t) based on the additional reactive power (ΔQ_m) which must be less than reactive power delivered by node-2 before compensation (Q_m^o).

TABLE III. Type, Size and Number of Shunt Capacitor Banks Placed at Node-2 for 15-Node Test System

Type	Size (KVAR)	Node-2
Fixed	900	1 No.
Switched	150	1 No.
	300	1 No.

A fixed type of capacitor bank with a net rating of 900 KVAR is permanently connected at node-2 to supply reactive power at light loading condition. Switched capacitor banks ranging from 150 KVAR to 300 KVAR are connected, to offer additional reactive power. The system minimum and maximum reactive power demands are 625 KVAR and 1375 KVAR respectively. The size type and No. of capacitor banks required is based on the variation of reactive power demands.

TABLE IV. Performance of the CP Algorithm Before and After Capacitor Placement at Node-2 for 15-Node Test System

Load Level	Before CP			After CP		
	L^{low}	V^{low}	Loss (KW)	L^{low}	V^{low}	Loss (KW)
Light Load	0.9603	0.9807	9.48	0.9738	0.9851	5.98
Medium Load	0.9361	0.9688	24.74	0.9576	0.9756	15.62
Full Load	0.9197	0.9608	39.18	0.9472	0.9698	24.52
Over Load	0.9115	0.9567	47.73	0.9419	0.9668	29.78

It is observed here at full loading condition the lowest VSI value of 0.9197 before Capacitor Placement is enhanced to 0.9472, in addition to improving the voltage profile from 0.9608 to 0.9698 besides reducing system losses from 39.18 KW to 24.52 KW.

B. *CASE-2 85- Node Test System*

TABLE V. VSI Values Before Compensation for 85- Node Test System

NODE No.	Light load	Medium load	Full load	Over load
2	0.9917	0.9862	0.9824	0.9804
3	0.9876	0.9796	0.9739	0.9710
4	0.9842	0.9739	0.9666	0.9627
5	0.9923	0.9871	0.9834	0.9815
6	0.9723	0.9539	0.9407	0.9337
7	0.9829	0.9713	0.9629	0.9585
8	0.9259	0.8762	0.8402	0.8212
9	0.9951	0.9904	0.9862	0.9838
10	0.9929	0.9880	0.9843	0.9823
11	0.9945	0.9906	0.9878	0.9862
12	0.9954	0.9922	0.9898	0.9885
13	0.9980	0.9966	0.9956	0.9950
14	0.9994	0.9990	0.9986	0.9985
15	0.9996	0.9994	0.9992	0.9991
16	0.9993	0.9989	0.9986	0.9985
17	0.9869	0.9790	0.9737	0.9710
18	1.0000	1.0000	1.0000	1.0000
19	0.9988	0.9980	0.9975	0.9972
20	0.9985	0.9976	0.9970	0.9967
21	0.9986	0.9977	0.9972	0.9969
22	1.0000	1.0000	1.0000	1.0000
23	0.9673	0.9475	0.9343	0.9276
24	0.9891	0.9821	0.9772	0.9747
25	0.9841	0.9731	0.9651	0.9609
26	0.9890	0.9820	0.9771	0.9745
27	0.9949	0.9916	0.9892	0.9880
28	0.9915	0.9860	0.9822	0.9802
29	0.9913	0.9857	0.9817	0.9797
30	0.9959	0.9932	0.9914	0.9904
31	1.0000	1.0000	1.0000	1.0000
32	0.9979	0.9964	0.9953	0.9947
33	0.9911	0.9852	0.9810	0.9788
34	0.9951	0.9918	0.9894	0.9882
35	0.9913	0.9856	0.9815	0.9794
36	1.0000	1.0000	1.0000	1.0000
37	0.9983	0.9970	0.9959	0.9953
38	0.9991	0.9984	0.9978	0.9975
39	0.9919	0.9862	0.9821	0.9799
40	0.9902	0.9836	0.9788	0.9762
41	0.9997	0.9994	0.9992	0.9991
42	0.9998	0.9997	0.9996	0.9996
43	0.9893	0.9822	0.9773	0.9747
44	0.9911	0.9853	0.9812	0.9791
45	0.9987	0.9978	0.9971	0.9967
46	0.9998	0.9997	0.9996	0.9995
47	0.9974	0.9957	0.9945	0.9939
48	0.9953	0.9921	0.9898	0.9886
49	0.9990	0.9981	0.9974	0.9970
50	0.9993	0.9989	0.9985	0.9984
51	0.9967	0.9945	0.9930	0.9922
52	0.9940	0.9899	0.9870	0.9855
53	0.9992	0.9986	0.9982	0.9979
54	1.0000	1.0000	1.0000	1.0000
55	1.0000	1.0000	1.0000	1.0000
56	1.0000	1.0000	1.0000	1.0000
57	0.9882	0.9806	0.9754	0.9727
58	0.9997	0.9994	0.9991	0.9990
59	0.9918	0.9863	0.9824	0.9804
60	0.9898	0.9832	0.9786	0.9762
61	0.9985	0.9975	0.9967	0.9963
62	1.0000	1.0000	1.0000	1.0000
63	0.9944	0.9908	0.9883	0.9870
64	0.9997	0.9994	0.9992	0.9991
65	0.9977	0.9962	0.9951	0.9946
66	0.9966	0.9944	0.9929	0.9921
67	0.9887	0.9813	0.9762	0.9736
68	0.9957	0.9929	0.9910	0.9900
69	0.9989	0.9982	0.9976	0.9974
70	0.9995	0.9991	0.9989	0.9988
71	1.0000	1.0000	1.0000	1.0000
72	0.9972	0.9953	0.9940	0.9933
73	1.0000	1.0000	1.0000	1.0000
74	0.9995	0.9991	0.9988	0.9987
75	0.9970	0.9950	0.9936	0.9929
76	1.0000	1.0000	1.0000	1.0000
77	1.0000	1.0496	1.0000	1.0000
78	0.9712	0.9528	0.9402	0.9337
79	1.0000	1.0000	1.0000	1.0000
80	0.9978	0.9964	0.9954	0.9949
81	0.9987	0.9978	0.9972	0.9969
82	0.9999	0.9999	0.9998	0.9998
83	0.9996	0.9993	0.9991	0.9990
84	0.9990	0.9989	0.9987	0.9986
85	0.9985	0.9983	0.9981	0.9980

It can be observed that only at node-8, VSI value is less than threshold value (L^t) and all other nodes, VSI values are above threshold value (L^t). Hence node-8 is selected as Candidate node for Compensation.

TABLE VI. Reactive Power Delivered Before Compensation (Q_m^o) and Requirement of VAR Compensation at Node-8 for 85-Node Test System

Load Level	Reactive Power Delivered Before Compensation (Q_m^o) at Node-8 (KVAR)	Requirement of VAR Compensation at Node-8 (KVAR)
Light Load	1032	900
Medium Load	1651	1650
Full Load	2063	1950
Over Load	2269	2250

It is observed here for the light, medium, full, and over loading conditions loading condition at node-8, VAR compensation is required as the VSI values are less than the threshold limit. The VAR compensation is based on the additional reactive power (ΔQ_m) which must be less than reactive power delivered by node-2 before compensation (Q_m^o).

TABLE VII. Type, Size and Number of Shunt Capacitor Banks Placed at Node-8 for 85-Node Test System

Type	Size (KVAR)	Node-8
Fixed	300	1No.
	900	1 No.
Switched	150	1 No.
	300	1 No.
	600	1 No.

A fixed type of capacitor banks with a net rating of 1200 KVAR is permanently connected at node-8 to supply reactive power at all loading conditions. Switched capacitor banks ranging from 150 KVAR to 600 KVAR are connected, which are required to offer additional reactive power. The system minimum and maximum reactive power demands are 1311 KVAR and 2884 KVAR respectively.

TABLE VIII. Performance of the CP Algorithm Before and After Capacitor Placement at Node-8 for 85-Node Test System

Load Level	Before CP			After CP		
	L^{low}	V^{low}	Loss (KW)	L^{low}	V^{low}	Loss (KW)
Light Load	0.9259	0.9378	69.90	0.9486	0.9508	42.37
Med-ium Load	0.8762	0.8968	192.07	0.9162	0.9209	111.81
Full Load	0.8402	0.8673	316.22	0.9026	0.8981	182.74
Over Load	0.8212	0.8519	393.50	0.8808	0.8895	222.17

It is observed here at full loading condition, the lowest VSI of 0.8402 before CP is enhanced to the level of 0.9026 besides reducing the losses from 316.22 to 182.74 KW and improving the voltage profile from 0.8673 to 0.8981.

IV. CONCLUSIONS

A Capacitor Placement algorithm for determination of optimal location, size, type and number of Shunt Capacitor Banks to be placed in Radial Distribution Systems for voltage stability enhancement, besides improving the voltage profile and reducing the system losses is presented. This Capacitor Placement algorithm finds the optimal locations of shunt capacitor banks by the calculated value of Voltage stability Index (VSI). The size, type and number of shunt capacitor banks to be placed are determined by the variation of reactive power demands in the system.

To carryout distribution power flow, a Network Topology Based Load Flow method is used in this work. Two matrices are developed based on the topological structure of distribution systems - The Bus Injection to Branch Current (*BIBC)* matrix and Branch Current Bus Voltage (*BCBV)* matrix. Time-consuming procedures, such as Lower Upper (LU) factorization and forward/backward substitution of the Jacobian matrix are not needed, and the ill-conditioned problem which occurs at the Jacobian matrix does not exist in the solution procedure. Therefore, this method is robust, economical and simple for calculations.

The case studies on the 15 and 85 Node Test Systems are carried out in light, medium, full as well as over loading conditions. Results show that there is improvement of voltage profile of the system, reduction of losses in the system and enhancement of Voltage Stability which is indicated by increased values of Voltage Stability Index (VSI). It is therefore clear that the optimal capacitor placement algorithm with Network Topology based distribution power flow/load flow enhances voltage stability, improves voltage profile and reduces the system losses in radial distribution systems.

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