AN ELEGANT VAR SUPPORT ALGORITHM FOR VOLTAGE STABILITY ENHANCEMENT OF DISTRIBUTION SYSTEMS

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Abstract : *The operating conditions of the present day distribution systems are closer to the voltage stability boundaries due to the ever-increasing load demand. Capacitors are commonly provided in distribution systems to offer the required VAR support with a view to minimise line losses and improve the voltage profile. A new algorithm for optimal locations and sizing of static and/or switched shunt capacitors in order to enhance voltage stability in addition to improving the voltage profile is proposed in this article. Test results on 33 and 69-node distribution systems are presented to demonstrate its effectiveness.*

Key words: voltage stability, radial distribution systems, capacitor placement.

Nomenclature

ACP	after capacitor placement
BCP	before capacitor placement
L_m	VSI of node-m
L^t	threshold value for VSI
L^{low}	lowest value of VSI in the system
nn	number of nodes in the system
PA	proposed algorithm
$P_m + jQ_m$	real and reactive powers at the receiving end of branch-m
$P_{L-m} + jQ_{L-m}$	real and reactive power load at node-m
$Q_m{}^o$	value of Q_m before compensation
$Q_{L-\min}$ and $Q_{L-\max}$	system minimum and maximum reactive power demands respectively
Qc_m	net reactive power compensation at node-m
$r_m + jx_m$	resistance and reactance of branch-m connected between nodes-k and m
VM	voltage magnitude
VS	voltage stability
VSI	voltage stability index
V^{low}	lowest value of VM in the system
V_k	voltage magnitude at node-k
δ_k	voltage angle at node-k
δ_{km}	$\delta_k - \delta_m$
Ψ	set of branches leaving node-m
ΔL_m	$L^t - L_m$, mismatch of VSI at node-m
ΔQ_m	additional reactive power compensation required at node-m
Φ_m	power factor angle of the receiving end power at branch-m
η	weighting factor

1. Introduction

Changes in the energy market have introduced new requirements for the operation and control of power systems. The objectives in this new environment are a higher return on investment and a more efficient exploitation of the existing network infrastructure, which result in congestions of the transmission grids with the consequence of operating the system closer to the voltage stability margin. These changes unwittingly drive the system towards the brink of voltage collapse. The phenomenon of voltage instability in power systems is characterised by a monotonic voltage drop, which is slow at first and becomes abrupt after some time; and is generally triggered by some form of disturbance or change in operating conditions that create an increased demand for reactive power that is in excess of what the system is capable of supplying.

Voltage instability was most probably one of the root causes for the US/Canada blackout, the Scandinavian blackout and the Italian blackout, which all happened in 2003. The problem of voltage instability has thus become a matter of serious concern for the system operators and is the subject of considerable investigation because of its importance in terms of the security of the system and the quality of the power [1-2]. In certain industrial areas, it has been observed that under certain critical loading conditions, the distribution system suffers from voltage collapse. In 1997, a voltage instability problem in a distribution network, which spread to a corresponding transmission system, had caused a major blackout in the S/SE Brazilian system [3]. The voltage stability (VS) problem of radial distribution system from its single line equivalent has been investigated and the voltage stability index (VSI) for identifying the node that is most sensitive to voltage collapse has been developed [4-8]. Therefore over the years, voltage stability of distribution systems has received great attention with a need for both analysis and enhancement of the operating conditions.

Capacitors are commonly used to provide VAR support in distribution systems. The amount of reactive compensation provided is very much related to the placement of capacitors in distribution feeders. The determination of the location, size, number and type of capacitors to be placed are of great significance, as it reduces power and energy losses, increases the available capacity of the feeders and improves the feeder voltage profile. Numerous capacitor placement (CP) methods for minimising losses have been suggested in the literature [9-18]. A CP algorithm with a view to enhance the reliability of the distribution system has been proposed [19]. Optimal allocation and sizing of capacitor banks for profitability and voltage enhancement of PV system on feeders has been proposed [20]. Algorithms for enhancing voltage stability of transmission systems by optimal CP have been discussed [21-22]. A relationship between voltage stability and loss minimisation has been developed and a strategy to maximise voltage stability through loss minimisation has been outlined [23-24]. However, there is still a need to device better techniques of capacitor placement in order to enhance voltage stability in distribution systems.

The objective of this article is to identify the extent of VAR support and develop a new methodology for optimal placement of static and/or switched shunt capacitors in radial distribution system for voltage stability enhancement based on the VSI suggested in [8] in addition to improving voltage profile and reducing system losses.

2. Proposed Methodology for CP

The method uses VSI suggested in [8] and offers reactive power support at the candidate nodes to improve VSI values towards a fixed threshold value, which is chosen based on the system configuration and the operating state. The proposed algorithm (PA) computes the amount of VAR requirements for voltage stability enhancement. There from, it appropriately determines the number, sizes, locations and types for capacitors to be placed on a distribution system.

The VSI that varies between unity at no load and zero at voltage collapse point at node-*m*, shown in Fig.1, can be determined by

$$L_m = V_k^{\,4} - 4\{P_m x_m - Q_m r_m\}^2 - 4\{P_m r_m - Q_m x_m\}V_k^{\,2} \qquad (1)$$

where P_m and Q_m are real and reactive powers at the receiving end of branch-*m*, respectively.

Eq. (1) may be written in terms of reactive power by replacing P_m by $Q_m \cot\Phi_m$ as,

$$L_m = V_k^{\,4} - 4\{x_m Q_m \cot\Phi_m - Q_m r_m\}^2 - 4\{r_m Q_m \cot\Phi_m + Q_m x_m\}V_k^{\,2} \qquad (2)$$

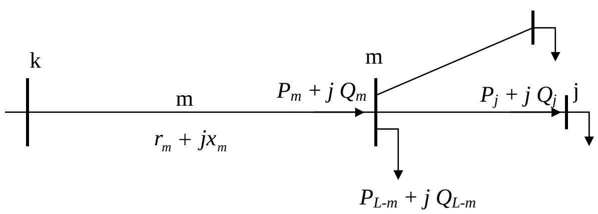


Fig. 1 Sample Distribution Line

When Q_m is perturbed by a small change, ΔQ_m, the change in L_m can be written as

$$\Delta L_m = a\,\Delta Q_m{}^2 + b\,\Delta Q_m + c \qquad (3)$$

where

$$a = 4\{x_m \cot^2 \Phi_m + r_m{}^2 - 2x_m r_m \cot \Phi_m\}$$
$$b = 2\,a\,Q_m + 4\{r_m \cot \Phi_m + x_m\}V_k{}^2 \qquad (4)$$
$$c = \Delta L_m$$

Eq. (3) is a simple quadratic equation and can be solved for ΔQ_m for the required change ΔL_m to bring the system away from the voltage instability region. The VSI at all the nodes are computed using Eq. (1). If all these values are greater than a fixed threshold value, it indicates that the system is away from the voltage instability point and it 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 having the lowest VSI value is chosen as the optimal node-m for capacitor placement and the additional reactive power compensation, ΔQ_m, to be provided at this node can be obtained by solving Eq. (4). However, the solution can be refined by multiplying ΔQ_m by a weighting factor η, which is chosen in between 0 and 1. The calculated reactive power support is provided at node-m and the above procedure is continued till all the VSI values become less than the threshold value.

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,

$$Qc_m \le Qm^o \qquad (5)$$

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, according to the following conditions.

The fixed and switched capacitor banks are chosen such that fixed capacitors when $\left\{\sum_{m=2}^{nn} Q_{L-m} \le Q_{L-\min}\right\}$ and switched capacitors when $\left\{Q_{L-\min} \le \sum_{m=2}^{nn} Q_{L-m} \le Q_{L-\max}\right\}$ have to provide VAR support. The flow chart of the PA is shown in Fig. 2

The algorithm of the proposed method is summarized as follows:

1. Read the system data.
2. Choose a fixed threshold value, L^t and set $\text{flag} = 0$ for all the nodes.
3. Carryout distribution power flow.
4. Compute VSI values, L_m, at all nodes using Eq. (1).
5. Choose the node having lowest value of VSI, L^{low}, as the sensitive node-m for capacitor placement.
6. If $L^{low} \ge L^t$, or if $\text{flag} = 1$ for all the candidate nodes, then go to step (10).
7. Solve Eq. (3) for ΔQ_m and then compute the net compensation at node -m
   $$Qc_m = Qc_m + \eta\,\Delta Q_m$$
8. Check for reactive power compensation limit:
   If $Qc_m \ge Q_m{}^o$, then $Qc_m = Q_m{}^o$ and set $\text{flag} = 1$ for node-m to avoid this node in the subsequent computations.
   and go to step (3).
9. The optimal locations for capacitor placement are obtained. Choose the nearest available value of capacitor from the computed values of Qc_m.
10. Considering $Q_{L-\min}$, Q_{Cm} and $\sum_{i=2}^{nn} Q_{L-m}$ choose the type of capacitor
11. Stop.

3. Simulation

The proposed algorithm is tested on 33 and 69-node distribution systems. The line and load data for these two systems are obtained from the references [25] and [26]. The power flow suggested in [27] is used in this study. The size of the capacitor banks considered in this study are 150, 300, 450, 600 and 900 kVAR. The results are obtained for light, medium, full and over load conditions by multiplying the base-load by a factor 0.5, 0.8, 1.0 and 1.1 respectively. The threshold value for VSI is taken as 0.79 and 0.70 for 33 and 69-node systems respectively. The threshold value depends on the power system configuration and the operating state. If this value is fixed too low, it does not ensure that the power system will be maintained in a stable state. If this value is fixed too high, the reactive power to be provided will be too excessive.

Table 1 Requirement of VAR compensation for 33-node system

kVAR requirement								
Node No.		13	14	15	16	30	31	32
Load Level	Light	---	---	---	---	---	---	---
	Medium	---	150	---	---	---	---	150
	Full	150	150	150	150	750	150	150
	Overload	300	150	150	150	900	300	150

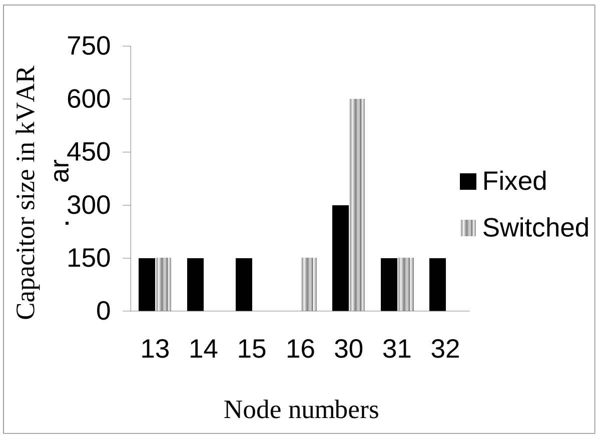
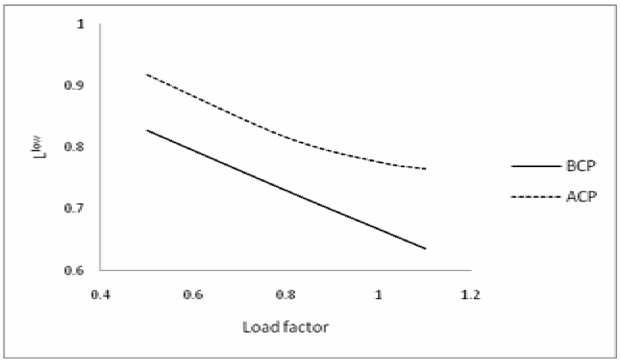


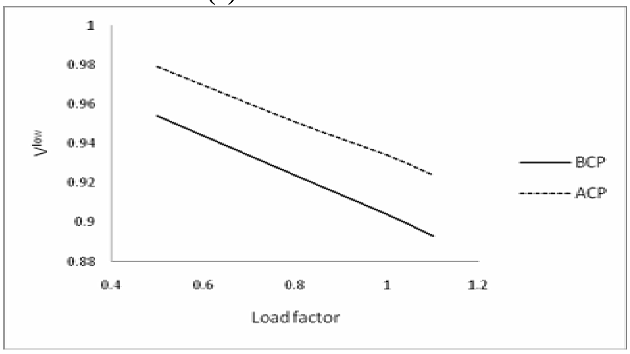
Fig. 2 Type and Size of capacitors placed for 33-node system

Table 2
Requirement of VAR compensation for 69-node system

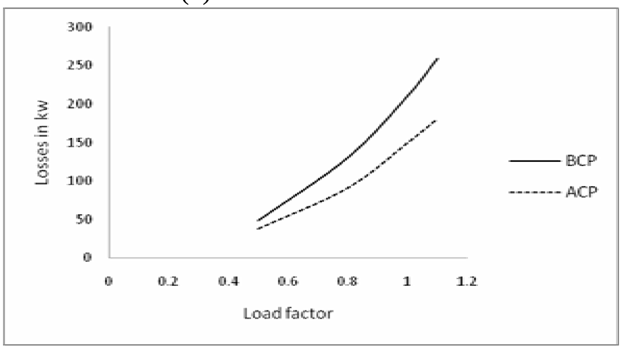
kVAR requirement					
Node No.		61	62	63	64
Load Level	Light	---	---	---	---
	Medium	---	---	150	150
	Full	1050	300	150	150
	Overload	1200	300	300	150



(a) L^{low} vs Load factor



(b) V^{low} vs Load factor



(c) Loss vs Load factor

Fig. 3 Performance Curves of 33-node system

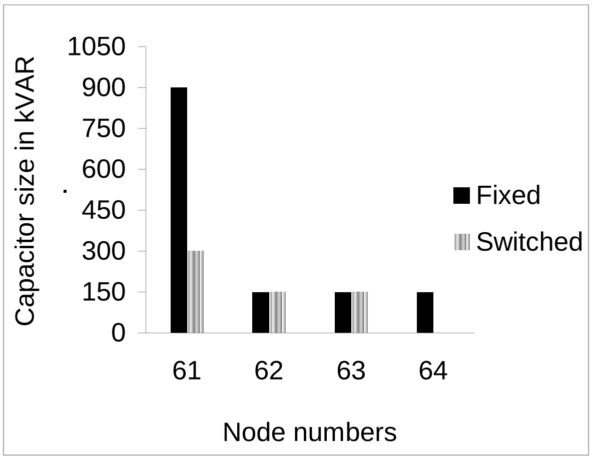
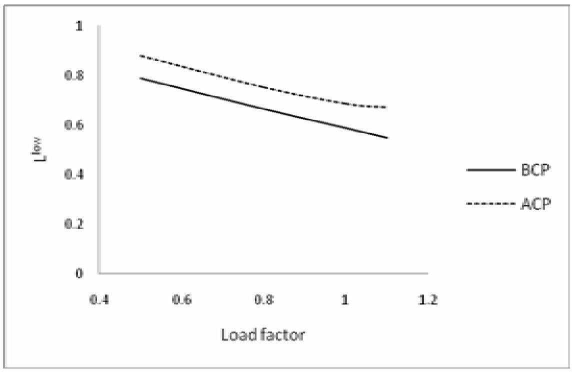
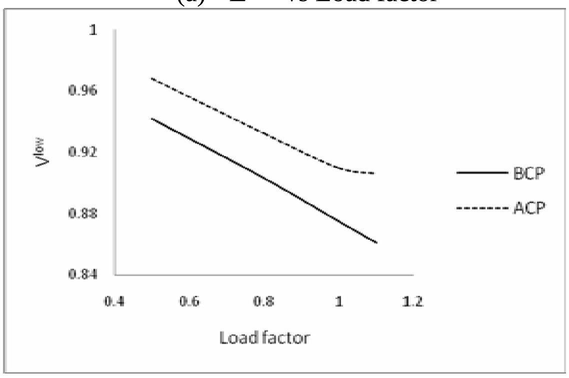


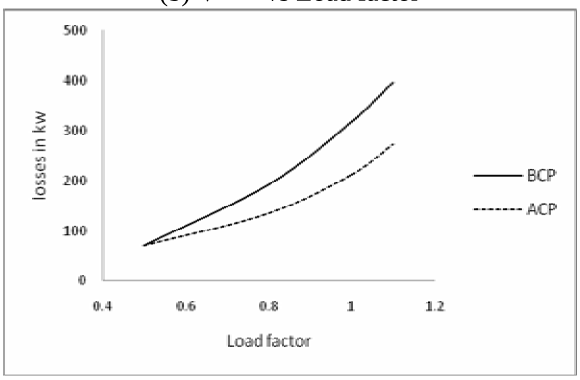
Fig. 4 Type and Size of capacitors placed for 69-node system



(a) L^{low} vs Load factor



(b) V^{low} vs Load factor



(c) Loss vs Load factor

Fig. 5 Performance Curves of 69-node system

33 node test system: The minimum VAR support required to enhance voltage stability for different loading conditions for 33 node system are given in Table-1. The system minimum and maximum VAR demands are 1150 kVAR and 2530 kVAR respectively. The size and type of capacitor banks required for 33 node system based on the variation of reactive power demands are given in Fig.2. Four fixed type of capacitor banks with a net rating of 1050 kVAR are permanently connected at nodes-13, 14, 30 and 32 to supply reactive power at all loading conditions. A switched capacitor with a rating of 150 kVAR each at nodes-13, 15 and 16 and two such units at nodes-30 and 31 are connected as shown in Fig. 2. The variation of L^{low}, V^{low} and the system losses with respect to different loading conditions before and after capacitor placement are graphically depicted in Fig. 3. These graphs clearly indicate that the optimal capacitor placement enhances voltage stability, improves voltage profile and reduces the system losses.

69 node system: The minimum and maximum reactive power demands for 69 node system are 1347 kVAR and 2964 kVAR respectively. The required reactive power compensation, size and type of capacitor banks before and after capacitor placement are given in Tables 2 and Fig. 4 respectively. The performance curves to relate the L^{low}, V^{low} and the system losses with respect to different loading conditions before and after capacitor placement are displayed in Fig. 5. These results also reveal that there is a significant improvement in system performance in terms of voltage stability, voltage profile and system losses.

4. Conclusion

An efficient VAR support algorithm that ensures optimal locations and sizing of static and/or switched capacitor banks in order to enhance voltage stability of radial distribution system has been developed. This method improves the voltage profile and reduces the system losses in addition to enhancing voltage stability. The approach is suitable for practical implementation on systems of any size.

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