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Original Contribution

OPTIMAL CAPACITOR PLACEMENT FOR POWER LOSS REDUCTION AND VOLTAGE STABILITY ENHANCEMENT IN DISTRIBUTION SYSTEMS

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ABSTRACT

In distribution systems, shunt capacitors are used to reduce power losses, to improve voltage profile, and to increase the maximum flow through cables and transformers. This paper presents a new method to determine the optimal locations and economical sizing of fixed and/or switched shunt capacitors with a view to power losses reduction and voltage stability enhancement. General Algebraic Modeling System (GAMS) [1] has been used to solve the maximization modules using the MINOS optimization software with Linear Programming (LP) .The proposed method is tested on 33 node distribution system and the results show that the algorithm suitable for practical implementation on real systems with any size.

Key words: Capacitor placement; Power losses; Voltage stability; Radial distribution systems

INTRODUCTION

Inability to provide reactive power demand will be caused to power losses and voltage instability. In recent years the active power demands have sharply increased and the system operating conditions are near to voltage stability boundaries. Therefore the voltage instability will be easily occurred by some form of disturbances or changes in operating condition that create an increase demand for reactive power. Capacitors are commonly used to provide reactive power support in distribution systems. The general capacitor placement problem is how to optimally determine the location and sizes of capacitor to be installed at buses of radial distribution systems. The approach to answer to this question has been changing different from past up to now, because the power system structure has changed from VIU (Vertically Integrated Utility) to restructured or deregulated power system. In the new environment each part of power system (Generation, Transmission and Distribution) acts as an independent section, which tries to maximize its profit.

Many researchers have been done on optimal capacitor placement problems. [2-7] solved this problem in view of minimizing losses. [8-9] developed a relation ship between voltage stability and loss minimization concerns. [10-11] presented algorithms for enhancing voltage stability of transmission systems by optimal capacitor placements. [12] presented a method based on GA to determine the optimal capacitor placement in unbalance radial distribution networks to minimize power losses. [13] developed an algorithm for optimal locations and sizes of shunt capacitors considering voltage stability enhancement. However, there is still a need to devise better techniques for capacitor placement in order to enhance voltage stability and to reduce power losses, with regard to

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restructured power systems. This paper proposes a new method to determine the optimal size and location of capacitors not only based on voltage stability improvement and power losses reduction, but also based on profit maximization in distribution systems. The proposed method is tested on 33 nodes radial distribution system and the results are presented.

Problem formulation

As mentioned before, capacitors are commonly used to provide reactive power support in distribution systems, which minimize line losses and improve voltage stability. Therefore the approach is to find the best locations and sizes of capacitors based on both power losses indices (PLI) [12] and voltage stability index (VSI) [13].

Threshold values for VSI and PLI should be optimally chosen to maximize the obtained profit of distribution systems, which is formulated as:

$$profit = \rho_e.T.(P_{loss}^{b} - P_{loss}^{a}) - \alpha(IC.No + \sum_{i=1}^{No} \rho_c.C_i) \tag{1}$$

For a typical radial distribution system shown in **Figure 1**, the VSI index that varies between unity at no load condition and zero at voltage collapse point can be determined at any node e.i. node m according to the following formula [13]:

$$L_m = V_k^4 - 4\,[P_m x_m - Q_m r_m]^2 - 4\,[P_m r_m + Q_m x_m]\,V_k^2 \tag{2}$$

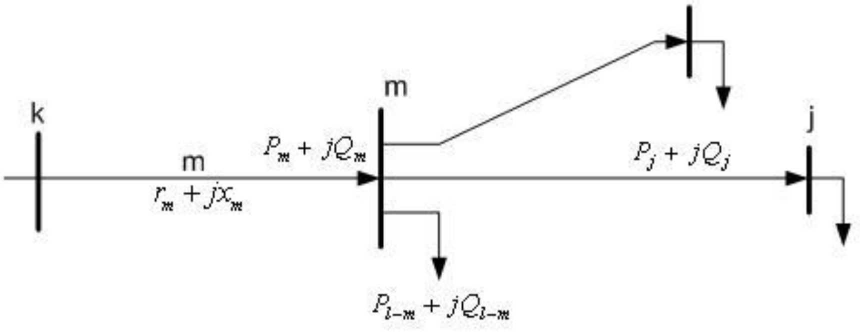

Figure 1. A reduced part of distribution system.

Installing a capacitor at node m will obviously improve VSI index with changing the reactive power flow in line k-m. Since required change in Q_m is measure of capacitor to be placed at node m, the additional reactive power compensation, ΔQ_m, to be provided at this node can be obtained by the following equations:

$$\Delta L_m = \frac{\partial L_m}{\partial Q_m}.\Delta Q_m \tag{3}$$

where,

$$\Delta L_m = L^t - L_m \tag{4}$$

$$\frac{\partial L_m}{\partial Q_m} = 8\,[P_m.r_m x_m - Q_m.r_m^2 - 0.5x_m.V_k^2] \tag{5}$$

If L_m value is greater than L^t, it indicates that the system is away from the voltage instability at that point. It should be reminded that the maximum compensation at each node is limit to the initial reactive power flow on line k-m prior to any compensation.

$$Q_{cm} \le Q_m^o \qquad (6)$$

Obviously installing capacitors based on VSI, will reduce power losses on the system, however the loss may be reduced more by additional compensations. Thus another index is required to reflect the need of additional reactive power compensation versus power loss reduction at any bus. To identify such conditions, nodal power loss index as defined by the following equation is therefore applied to the system.

$$PLI(k) = \frac{PL(k) - PL^{\min}}{PL^{\max} - PL^{\min}} \quad \forall k = 2,3,...,n \qquad (7)$$

where PL(k) denotes loss reduction after capacitor installation at node k. If PLI(k) is greater than a pre specified value PL^t, that node is a good candidate for locating new capacitors.

The proposed method

To determine the number, size, location and type of capacitors to be placed on a distribution system, the following steps should be performed:

Step 1: Read system data

Step 2: Solve distribution power flow equations and calculate the VSI value, L_m, at all nodes as well as based case total active power losses.

Step 3: For the weak buses improve VSI values by injecting reactive power toward a fixed threshold value, L^t.

Step 4: Perform cost-benefit analysis (eq(1)) and scale L^t up.

Step 5: Repeat step 3 to 5 until profit is maximized.

Step 6: Calculate the total active power loss of the system and active power loss index for every bus, PL, after compensation based on VSI.

Step 7: Reduce power loss toward a fixed PL^t value.

Step 8: Perform cost-benefit analysis and scale PL^t up to one.

Step 9: Repeat step 7 to 9 until profit is maximized.

Step 10: Stop and report the final solution.

Figure 2 shows the flowchart of the proposed method in more details.

Simulation results

The proposed method is performed on 33 node distribution system, whose characteristic including load and line data are given in [14-16].The results are simulated for high, medium, full and over load conditions by multiplying the base load by factor 0.5, 0.8, 1 and 1.1 respectively. The initial threshold value for VSI and PLI is taken as 0.5 and 0.2. The economical data necessary for profit calculation are given in **Table 1.**

Table 1. *Economical data*

ρ_c ($)	IC ($)	Average Energy Price ρ_e ($/KWh)			
		Light Load	Medium Load	Full Load	Over Load
5	1250	0.06	0.075	0.08	0.09

The proposed algorithm is performed on the test system and it is terminated when optimum threshold values for PLI and VSI are obtained. The obtained L^t and PL^t are 0.85 and 0.45 respectively.

The minimum reactive power compensations based on these results are given in table II for different loading conditions. In **Table 2** all nodes except node 18 are candidate through VSI and node 18 is added on PLI. Although the PLI procedure changes the size of capacitor banks in the some candidate nodes based on VSI.

Table 2. *Requirement of VAR compensation*

Node No.		13	14	15	16	18	30	31	32
Load level	Light	-	-	-	-	-	-	-	-
	Medium	-	150	-	-	150	-	150	150
	Full	150	150	150	150	150	600	150	150
	Over	300	150	150	150	150	900	300	150

The size and type of capacitor banks based on the variation of reactive power demand **(Table 3)** are given in Table 3 where the typical capacitor banks used in this study are integer product of 150 Kvar.

Table 3. *Performance of proposed method*

Load level						
	L^{low}	V^{low}	Loss (KW)	L^{low}	V^{low}	Loss (KW)
Light	0.828	0.955	49	0.903	0.980	33.5
Medium	0.73	0.924	130.5	0.803	0.953	85.3
Full	0.667	0.905	211	0.785	0.951	137.6
Over	0.636	0.895	260	0.780	0.94	175

Table 4 compares L^{low}, V^{low} and total power loss of system before and after capacitor installation at different load levels. The result shows that optimal capacitor placement reduces power losses and improves voltage stability.

The algorithm shown in **Figure 2** is performed on the system with fixing the threshold values of VSI and PLI on 0.9 and 0.45 respectively, where these values are not selected optimally. The results show that obtained profit in this case (21025.4$) is much lower than previous case (36013.15$), which satisfies the high performance of propose method in the restructures power system.

Table 4. *Type and size of capacitor placed*

Node No.		13	14	15	16	18	30	31	32
Fixed	150Kvar	1 No	1 No	-	-	1 No	-	1 No	1 No
	600Kvar	-	-	-	-	-	1 No	-	-
Switched	150Kvar	1 No	-	1 No	1 No	-	2 Nos	1 No	-

CONCLUSION

In this paper a new method has been presented for the optimal placement and sizing of capacitor banks in distribution systems. The proposed method enhances voltage stability, improves voltage profile, reduces power losses and maximizes profit. The effectiveness of the proposed method has been demonstrated through the 33 nodes system. The results show that optimally chosen the threshold values for VSI and PLI will maximize the obtained profit of distribution systems.

In this paper the transient effect of switching capacitors on the system are not considered, but the authors suggest that capacitors location should be determined based on Transient Recovery Voltage (TRV) of the system.

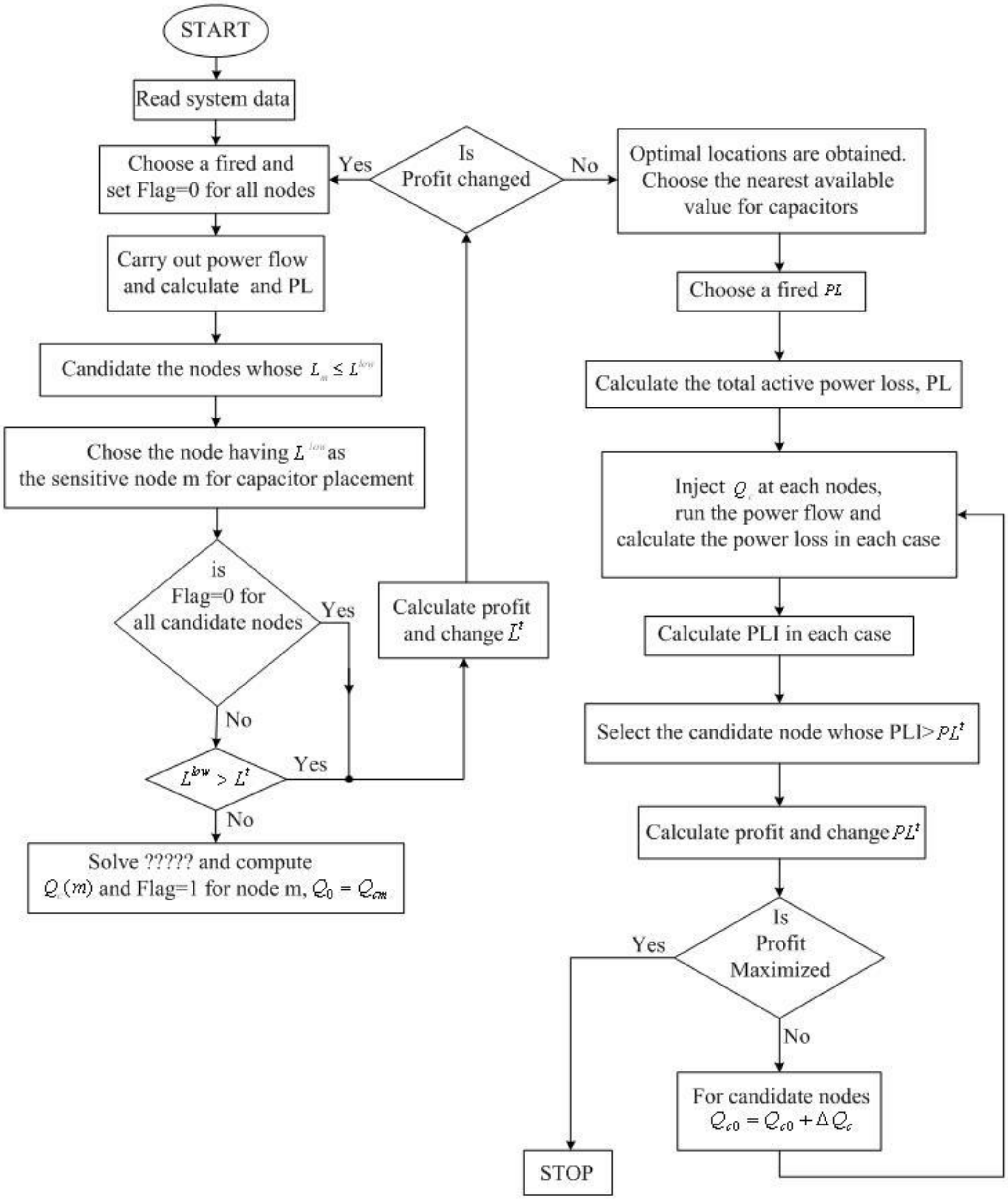

Figure 2. Flowchart of the proposed method.

Nomenclature

ρ_e	Energy price ($/Kwh)
T	Time period (8760 hrs)
p^b_{loss}	Active power loss before capacitor placement
p^a_{loss}	Active power loss after capacitor placement
α	Depreciation factor is 0.2
IC	Installation cost ($/ each location)
NO	No of capacitor nodes

ρ_C	Cost of capacitor ($/Kvar)
C_i	Capacitor bank rating (Kvar)
L_m	VSI value at node m
V_k	Voltage magnitude at node k
$P_m + jQ_m$	Real and reactive power at the receiving end of branch m
$r_m + jx_m$	Resistance and reactance of branch m connected between nodes k and m
$P_{l-m} + jQ_{l-m}$	Real and reactive power node m
L^t	Threshold value for VSI
Q_{cm}	Net reactive power compensation at node m

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