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Optimal Capacitor Placement and Sizing in Radial Distribution System

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Abstract:- Shunt capacitors are used for reactive power compensation to maintain voltage in a distribution system. The aim of the problem is to find an optimal location and size of capacitor to install on a distribution system. Determination of capacitor size is an optimization problem and the goal is to minimize overall cost of power loss as well as cost of shunt capacitors simultaneously while satisfying constraints. In this paper, capacitor placement is carried out using a Loss Sensitivity Factor method and the solution of capacitor sizing problem is achieved using Goal Attainment method. Optimization problem is solved with the help of MatLab and load flow is carried out using MiPower software.

Keywords:- Reactive power compensation, Optimization, Shunt capacitor, Goal Attainment method

I. INTRODUCTION

Shunt capacitors are used extensively for reactive power compensation to maintain voltage profile in a distribution system. The reactive power supplied by capacitor provides several benefits i.e. power loss reduction, voltage-profile improvement and power factor correction. The term reactive power compensation corresponds to compensate the lagging reactive current of the power system by supplying leading reactive current to the power system. This leading reactive power is supplied by shunt capacitors to the power system.

The pioneers of optimal capacitor placement, Neagle and Samson [1] used analytical approaches for capacitor placement. They gave 'two-third' rule for capacitor placement. The 'two-third' rule says that for maximum loss reduction capacitor should be installed at a position two thirds of the distance along the total feeder length. The method was based on assumption of a feeder with a uniformly distributed load. That's the reason why Loss Sensitivity Factor method is used for capacitor placement in this paper as the model taken in the paper is not having a uniformly distributed load.

The objectives for determination of capacitor sizing consist of two important terms, which are reduction of power losses and reduction of capacitor purchasing cost. These objectives conflict with each other in the sense that any improvement in one objective results into the decrement of the other objective. The aim of this problem is to find a compromise between the objectives for the satisfying solution of the problem. Optimization problem is solved by the goal-attainment method in this paper.

Two types of capacitors are usually considered: fixed and switched capacitor banks. Fixed banks are operating on the feeder all the time. In this paper, fixed capacitor banks are taken into account, optimal placement is determined using Loss Sensitivity Factors method, sizing is determined using Goal Attainment method with the help of MatLab[2] and load flow is carried out in MiPower[3] software.

II. SYSTEM MODEL

IEEE 13 Node Test Feeder model is considered for the simulation [4] and is shown in Fig. 1. Two cases of IEEE 13 Node Test Feeder are taken into account in this paper. First one is IEEE 13 Node Test Feeder with standard data and the other is IEEE 13 Node Test Feeder with 0.7 power factor data. For the second case, load data are changed accordingly. This is a model of a distribution system. Some assumptions have been taken according to the requirements. The model is simulated in MiPower[3] software.

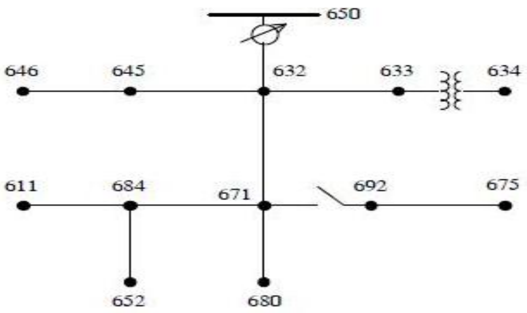

Fig. 1: IEEE 13 Node Test Feeder

III. PROBLEM FORMULATION

There are two cost functions conflicting in nature: cost of power losses and capacitor purchasing cost. Ideally a distribution utility should place a capacitor for reactive power compensation at every node so that active losses, reactive losses and therefore loading of line will reduce and performance of the system will improve, but practically it is not possible because of the cost limitation of the distribution utility. In the same way, when distribution utility doesn't place capacitors at all, cost of purchasing capacitor reduces but at the same time cost of power losses increases. So, it is required to find a trade-off between these two conflicting objectives. Considering a distribution line (kth -line) connected between 'p' and 'q' nodes. [5] A distribution line model is shown in Fig. 2.

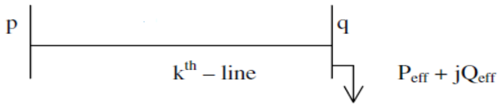

Fig. 2: A distribution line model

Total power losses of the system are given by Eq. (1).

$$[{I_k}^2] * [R_k] \tag{1}$$

Which can be expressed as Eq. (2).

$$P_{lineloss}\,[q] = \frac{(P[q]^2 + Q[q]^2) * [R_k]}{V[q]^2} \tag{2}$$

Where,

$P_{lineloss}\ [q]$ = Total power loss in kth line (watt)
$P[q]$= Total effective active power supplied beyond the node 'q' (watt)
$Q[q]$ = Total effective reactive power supplied beyond the node 'q'(var)
$V[q]$= Voltage at node 'q' (volt)
R_k= Resistance of kth line (ohm)
I_k= Current in the kth line (ampere)

The objective of optimization problem is to minimize cost of power losses and capacitor purchasing cost. Objective function (F) is given by Eq. (3). The first term of the objective function (F) represents the cost of power losses and the second term represents capacitor purchasing cost. Thus, the whole objective function is formulated in terms of cost. The objective function [6] can be formulated as

$$F = \min C_e \sum_{q=1}^{m} \frac{(P[q]^2 + (Q[q] - Q_c[q])^2)}{V[q]^2} * [R_k] + C_{c.} \sum_{q=1}^{m} Q_c[q] \tag{3}$$

Where,

F = Objective function
C_c = Capacitor purchasing cost (Rs / var)
C_e = Cost of energy (Rs / Wh)
m = Total number of nodes
$Q_c[q]$= Capacitor to be installed at 'q' (var)

A. Constraints

Inequality constraints [7] to be taken into account for capacitor sizing problem are shown by Eq. (4) and (5).
1) Voltage constraints:
The bus voltage magnitudes should lie within an acceptable range (±5%) throughout the optimization process. Voltage constraints are given in Eq. (4).

$$V_{min} \leq V \leq V_{max} \tag{4}$$

2) Capacitor size constraints:

It is necessary that the total reactive power injection by fixed capacitors should not exceed the total reactive power demand in the radial distribution system. Capacitor size constraint can be formulated as given by Eq. (5).

$$\sum_{q=1}^{nc} Q_c[q] \leq Q_T \tag{5}$$

Where,
nc = Total number of shunt capacitors to be installed in the distribution system
Q_T = Total reactive power demand

IV. METHODOLOGY FOR OPTIMAL LOCATION OF CAPACITOR

A methodology named Loss Sensitivity Factors (LSF) is used to determine candidate nodes for the placement of capacitors. The estimation of the potential nodes from this method reduces the search space for optimization [5]. Power losses for each node can be found by Eq. (2) and from that LSF can be determined. LSF can be obtained as shown in Eq. (6).

$$\frac{\partial P_{lineloss}}{\partial Q[q]} = \frac{(2 * [Q[q] * [R_k])}{V[q]^2} \tag{6}$$

Eq. (2) represents total line loss of the particular node. LSF for all the nodes can be calculated from Eq. (6).The LSF $(\partial P_{lineloss}/\partial Q)$ are calculated for each node from load flows and they are normalized in the range of 0-1. The obtained values are arranged in descending order for all lines of the distribution system. The descending order of $(\partial P_{lineloss}/\partial Q)$ will decide the sequence in which the buses are to be considered for compensation. This sequence is exclusively governed by the $(\partial P_{lineloss}/\partial Q)$ and hence the proposed method is called as ‘Loss Sensitivity Factors’ method. In this way, it is useful for determining the potential locations for capacitor placement.

At these buses, ‘normalized voltage’ magnitudes are calculated by considering the base voltage given by (‘Norm’= V(p.u.)/0.95). V(p.u.) represents per unit voltage magnitude. Buses whose ‘Norm’ value is < 1.01 are considered as buses requiring the capacitor placement. If ‘Norm’ value for the bus is >1.01, such bus needs no reactive power compensation. Table I represents LSF and ‘Norm’ values for the IEEE 13 Node Test Feeder with standard data. Table II shows LSF and ‘Norm’ values for IEEE 13 Node Test Feeder with 0.7 power factor data. ‘Loss Sensitivity factors’ value helps to decide the sequence in which buses are to be considered for compensation placement and the ‘Norm’ decides whether the buses needs reactive power compensation or not. From Table I, it can be seen that for the IEEE 13 Node Test Feeder with standard data, node to be considered for the placement of capacitor is {675} and for IEEE 13 Node Test Feeder with 0.7 power factor data, nodes to be considered for the placement of capacitors are {634,671,684,645,611} as shown in Table II .

Table I : LSF & Norm Values for IEEE 13 Node Test Feeder with Standard Data

Node	LSF	Norm
632	1.0000	1.0439
650	0.9725	1.0736
671	0.4053	1.0216
675	0.2457	1.0046
692	0.2441	1.0122
633	0.1444	1.0401
634	0.1443	1.0385
684	0.0858	1.0189
646	0.0657	1.0382
645	0.0655	1.0402
652	0.0446	1.0177
611	0.0415	1.0175
680	0	1.1058

Table II: LSF & Norm Values for IEEE 13 Node Test Feeder with 0.7 Power Factor Data

Node	LSF	Norm
634	1.0000	1.0059
632	0.0920	1.0381
650	0.0885	1.0338
671	0.0377	0.1190
675	0.0230	1.0338
692	0.0228	1.0314
633	0.0133	1.0736
684	0.0080	1.0064
646	0.0061	1.0111
645	0.0060	0.9905
652	0.0041	1.0111
611	0.0039	1.0078
680	0	0.9998

V. METHOD FOR OPTIMAL SIZING OF CAPACITOR

In this paper, Goal Attainment method of Gembicki [8] is used to determine capacitor sizing. It involves expressing design goals *i.e.* $\{F^* = F_1^*, F_2^*\}$ which is associated with objectives i.e. $\{F(x) = F_1(x), F_2(x)\}$.The problem formulation allows the objectives to be under or over achieved with respect to initial design goals. A vector of weights i.e. $\{w = w_1, w_2\}$ where $w_i > 0$ controls the degree of over or under achievement of the goals. The method is expressed as an optimization problem by the following formulation:

minimize γ
wrt x
such that

$$F_i(x) - w_i\gamma \le F_i^* \qquad i = 1, \ldots, m \tag{7}$$

The term $w_i\gamma$ introduces an element of slackness into the problem, which otherwise imposes that the goals must be solidly met. The vector of weights w makes designer (i.e. distribution utility) to express a measure of the relative trade-offs between the objectives. A set of goals that a designer (i.e. distribution utility) wishes to achieve for each objective function can be fixed. Eq. (7) shows that the method reduces the difference between the solution and the goal.

VI. SIMULATION RESULTS

Capacitor placement problem is solved with the help of MatLab software. MatLab Optimization Toolbox [2] is used to simulate capacitor sizing problem by Goal Attainment method. Capacitor size shown in Table III is placed on IEEE 13 Node Test Feeder and then load flow is carried out using MiPower software[3]. Capacitor sizes shown in Table IV are placed on IEEE 13 Node Test Feeder having 0.7 power factor and then load flow is carried out using MiPower software. Cost of energy is taken as 300 Rs / Mwh and cost of capacitor is taken as 75 Rs / kvar. Loss reductions after placing capacitor for IEEE 13 Node Test Feeder with standard data are shown in Table V and loss reductions after placing capacitor for IEEE 13 Node Test Feeder with 0.7 power factor are presented in Table VI. Improvements in voltage are shown in Table VII for both the cases.

Table III: Capacitor Size for IEEE 13 Node Test Feeder with Standard Data

Node	Capacitor size (kvar)
675	348.69

Table IV: Capacitor Sizes for IEEE 13 Node Test Feeder with 0.7 Power Factor Data

Node	Capacitor size (kvar)
634	373.59
671	1177.08
684	251.62
645	195.38
611	150.37

Table V: Loss Reductions by Implementing Capacitor for IEEE 13 Node Test Feeder with Standard Data

From Node	To Node	Without capacitor			With Capacitor		
		Active Power Loss(MW)	Reactive power Loss(MVAR)	Loading of Line (%)	Active Power Loss(MW)	Reactive power Loss(MVAR)	Loading of Line (%)
650	632	0.0958	0.0569	98.6	0.0869	0.0516	93.9
633	632	0.0015	0.0009	25.0	0.0015	0.0009	25.0
632	645	0.0014	0.0008	48.2	0.0014	0.0008	48.1
645	646	0.0004	0.0003	26.9	0.0004	0.0003	26.8
632	671	0.0541	0.0321	74.1	0.0478	0.0284	69.7
692	675	0.0062	0.0037	50.4	0.0048	0.0029	44.3
684	671	0.0008	0.0005	17.6	0.0008	0.0005	17.6
611	684	0.0002	0.0001	9.7	0.0002	0.0001	9.7
671	680	0.0000	0.0000	0.0	0.0000	0.0000	0.0
684	652	0.0002	0.0001	8.0	0.0002	0.0001	8.0
671	692	0.0095	0.0056	62.0	0.0073	0.0044	54.5
633	634	0.0001	0.0011	100.2	0.0001	0.0011	100.0

Table VI: Loss Reductions by Implementing Capacitor for IEEE 13 Node Test Feeder with 0.7 Power Factor Data

From Node	To Node	Without capacitor			With Capacitor		
		Active Power Loss(MW)	Reactive power Loss(MVAR)	Loading of Line (%)	Active Power Loss(MW)	Reactive power Loss(MVAR)	Loading of Line (%)
650	632	0.1458	0.0866	121.6	0.0789	0.0469	89.5
633	632	0.0021	0.0012	29.2	0.0010	0.0009	20.2
632	645	0.0021	0.0012	58.3	0.0013	0.0008	45.8
645	646	0.0007	0.0004	33.6	0.0007	0.0004	33.2
632	671	0.0843	0.0501	92.5	0.0461	0.0274	68.4
692	675	0.0101	0.0060	64.0	0.0098	0.0058	63.0
684	671	0.0012	0.0007	22.3	0.0006	0.0004	16.1
611	684	0.0004	0.0002	12.7	0.0002	0.0001	8.8
671	680	0.0000	0.0000	0.0	0.0000	0.0000	0.0
684	652	0.0002	0.0001	9.6	0.0002	0.0001	9.4
671	692	0.0145	0.0086	76.8	0.0141	0.0084	75.6
633	634	0.0002	0.0016	116.6	0.0001	0.0007	81.0

Table VII: Improvements in Voltage for IEEE 13 Node Test Feeder with Standard Data and with 0.7 Power Factor Data

Node	IEEE 13 Node Test Feeder with standard data		IEEE 13 Node Test Feeder with 0.7 power factor data	
	without capacitor V(p.u.)	with capacitor V(p.u.)	without capacitor V(p.u.)	with capacitor V(p.u.)
611	0.9666	0.9694	0.9557	0.9727
632	0.9917	0.9931	0.9862	0.9947
633	0.9881	0.9895	0.9821	0.9921
634	0.9866	0.988	0.98	0.9917
645	0.9882	0.9897	0.9821	0.9914
646	0.9863	0.9877	0.9798	0.9891
650	1.0199	1.0199	1.0199	1.0199
652	0.9668	0.9696	0.9561	0.9726
671	0.9705	0.9733	0.9605	0.9754
675	0.9544	0.9599	0.941	0.9562
680	0.9705	0.9733	0.9605	0.9754

684	0.9679	0.9708	0.9574	0.9739
692	0.9616	0.9658	0.9499	0.9649

Table VIII: Cost Calculations for IEEE 13 Node Test Feeder

Case	**Without capacitor(Rs)**	**With capacitor(Rs)**	**Capacitor cost(Rs)**	**Total cost(Rs)**	**Savings/ year**
IEEE 13 Node Test Feeder With standard data	447285	397879	26151	424031	23254
IEEE 13 Node Test Feeder with 0.7 power factor data	687484	402084	161103	563187	124297

VII. OBSERVATIONS AND DISCUSSIONS

It is observed that after determining optimal placement and sizing of capacitor, if it is placed on the distribution system at the determined optimal location and size, then it helps out in savings of cost. Table VIII shows cost reductions for both the cases IEEE 13 Node Test Feeder with standard data and IEEE 13 Node Test Feeder with 0.7 power factor data. By placing capacitor at optimal location with optimal size, improvement in voltage, reduction in line losses and reduction in line loading can be achieved. And hence, system performance improves and life of the conductors also increases. Also, savings in cost is beneficial for a distribution utility.

VIII. CONCLUSION

In this paper, a method for optimal capacitor placement and sizing problem is presented. By optimal placement and sizing of the capacitor on radial distribution system; line losses, line loading are reduced, voltage is improved and mainly savings in cost is achieved. Test results on IEEE 13 Node Test Feeder with standard data and IEEE 13 Node Test Feeder with 0.7 power factor data are presented in the paper. This method places capacitors at optimal locations on a distribution system with optimal sizes and offers savings in cost.

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