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Sensitivity Analysis Technique for Optimum Allocation of Capacitor Banks Considering Voltage Profile and Transmission Losses

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ABSTRACT
The problem of transmission loss minimization in electric power grids through capacitor bank (CB) installation at some influential busbars is one of the most major problems which gained importance in the field of power system design and analysis. This problem has been tackled in this paper. Capacitor installation at some influential busbars reduces reactive power flow through grid lines, consequently reduces the reactive component of the current flows and the real power losses due to this component. This paper proposes an efficient and straightforward approach which can determine the most appropriate busbar at which capacitor bank installation achieves maximum transmission loss reduction. Two factors are utilized for this purpose, the power loss sensitivity factor (PLSF) and the voltage sensitivity index (VSI). The first gives graded indication to the effect of reactive power flows on the total system losses whilst the second factor gives indication to the changes in voltage magnitudes due to CB installation. These two factors are then combined in one integrated factor used to arrange the system buses according to their effects on loss reduction. The benefit is shrinking the search space of the problem. The effectiveness of the proposed method is realized on a 35-bus sample system.

Keywords: *loss minimization; capacitor banks; sensitivity analysis; voltage profile.*

1. Introduction

Loss minimization in both transmission and distribution networks is a vital issue in the field of power systems design, operation, and control. As a matter of fact, appreciable quantities of power losses in power systems take place in distribution networks which are responsible of about 15% of the total system losses [1]. This ratio, compared with that of transmission networks which possess about 17% of the total losses is considered high since transmission networks are much more widely extended than distribution networks. This is due to the relatively low voltages-up to 66 kV-and high currents in these distribution networks. Moreover, the commonly used radial configurations in distribution networks contribute in raising the system losses [2]. In general, currents flowing through lines of distribution networks consist of active and reactive components which depend on the system loads beside lines' impendences. Both components contribute in line losses with quantities proportional to the square of magnitude of each component. Most of loads possess inherited lagging power factor currents and operate as inductive loads which give rise to voltage drops in busbar voltages. This is one of the unfavorable results caused by flowing reactive components of current through network lines. Moreover, such reactive components of line currents contribute in increasing line losses. In order to mitigate these drawbacks, reactive components of the line currents have to be minimized. This can be achieved by different methodologies such as installation of distributed generators [3-7], load balancing and network reconfiguration [8,9], and shunt capacitors installations [10-15]. Shunt capacitors are installed in distribution networks for the purposes of supporting voltage profile, controlling the flow of reactive power and reducing line losses. Methodologies used to determine the optimum locations and sizes of shunt capacitors for loss minimization and voltage enhancement include mathematical analytical programming [10,15], Artificial Intelligence techniques such as Expert Systems [3], Fuzzy-based approach [12], Particle Swarm optimization, and sensitivity analysis approach [8].

The present work is aiming at reaching some

influential busbars which achieve the maximum loss reduction by calculating two sensitivity factors; The first gives a measure of the sensitivity of line losses to changes in reactive power flows, while the second gives the sensitivity of the bus voltage to changes in network variables and parameters such as line resistances and reactances, bus voltages, and reactive power flows. These two factors are then combined in a single factor called composite sensitivity index (CSI) of the busbar. Changes in both voltages and reactive power flows are assumed due to the injected reactive power from shunt capacitors. By examining the values of the combined sensitivity factors for all buses, the most influential busses can be arranged descendingly.
The paper is arranged as follows:
Section 2 gives a description of the research significance. Problem description and the role of sensitivity analysis in the problem solution is introduced in section 3. PLSF is defined with explaination in section 4. Section 5 introduces the meaning and the method of utilization of VSI. Section 6 suggests a modification for the VSI to take account for voltage constrains. CSI is introduced in section 7. Steps of problem solution are given in section 8. Section 9 gives a case study. General conclusion is given in section 10.

2. Research Significance

One of the most important issues in the field of electrical power system is to get losses in all system components to the least possible level. Losses are created in generators, transformers, lines, loads, and some other system components such as protection and switchgear devices. Losses in system lines (transmission and distribution) contribute to more than 30% of the totals system losses. It is believed that line loss reduction is economical and easier than that of other system component. This is the motivation of the current research.

3. Problem Description

V_i: Voltage magnitude of bus i (kV),i=1,2,………..,n.

P_{Li} , Q_{Li}: Real and reactive components of load at bus i(Kw, Kvar) respectively
.

P_i , Q_i: Real and reactive power flows from bus i to bus k,(k=i+1)in kW and kVAR respectively.

R_{ik} , X_{ik} :Resistance and reactance of the line i-k (Ohms).
P_o , Q_o : Real and reactive power supplied from the source.

P_{Lik}, Q_{Lik}: Real and reactive losses in the section i-k (kW-kvar) respectively

P_{TL}:Total system losses.

As a general rule, any change in P_{Li} and/or Q_{Li} will yield changes in V_i , P_i , Q_i, P_o , Q_o, and P_{TL}.
Installation of shunt capacitor with rating is equivalent to reduction of with the capacitor rating, and consequently, reduction of reactive power flows in all feeder sections up to bus i by the same value. As a consequence, will decrease to a value of and the feeder bus voltages will rise. This rise may cause violation of the upper limits of some busbar voltages. The problem is how to find the optimum size and location of the shunt capacitor which achieves maximum total loss reduction whilst keeping all bus voltages within their lower and upper limits.

3.1 Sensitivity Analysis

Sensitivity Analysis is a method by which the degree of change of one variable of the system (affected element) due to certain action (active element) can be evaluated. The simplest form of this analysis is to get an algebraic relation between the affected element and the active element. Another method of the analysis is getting the rate of change of the affected element with respect to the change of the active element. The present work utilizes the two methods to get two sensitivity factors, one for power loss and the other for voltage variation of one bus with respect to voltage variation of another bus. The active element for both factors is the installation of capacitor bank at one busbar. This yields variation of both total system losses and magnitudes of busbar voltages.

4. Power Loss Sensitivity Factor (PLSF)

Consider the section i-k (k=i+1) in radial system of n nodes shown in Figure 1.

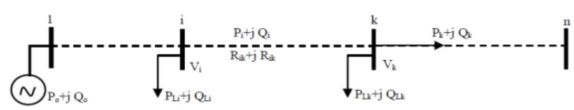

Figure 1- Feeder of a Radial System

In an n-node system. The real power loss in section i-k is given as:

$$P_{Lik} = \frac{P_k^2+Q_k^2}{V_i^2} R_{ik} \quad (1)$$

The total power loss in all feeder $P_{TL}$is given as:

$$P_{TL} = \sum_{i=1}^{n-1} P_{Lik} \quad (2)$$

The power loss sensitivity factor for the section i-k

(PLSF)i-k is ;

$$(\text{PLSF})_{i-k} = \frac{\partial P_L(i-k)}{\partial Q_k} = \frac{2Q_k}{V_i^2} R_{ik} \quad (3)$$

The total power sensitivity factor for the whole feeder due to CB installation at busbar k $(\text{PLSF})_{T(k)}$ is:

$$\frac{\partial P_{LT}}{\partial Q_k} = 2\sum_{j=1}^{k-1} \frac{2Q_{j+1}}{V_i^2} R_{j-j+1} = (\text{PLSF})_{T(k)} \quad (4)$$

This factor accounts for installation of the reactive power source at bus k. Factors are calculated for i=1,2,………., n-1 and arranged discerningly to get the priority of the capacitor installation regarding loss reduction.

5. Voltage Sensitivity Index (VSI)

VSI(k) is an index defined in [6] as a measure of sensitivity of voltage of busbar k to the flow (P_i+Q_i) from busbar i to busbar K. It is given by:

$$VSI(k) = |V_i|^4 - 4(P_k * X_{ik} - Q_k * R_{ik})^2 - 4(P_k * R_{ik} + Q_K * X_{ik}) * |V_i|^4 \quad (5)$$

This means that VSI(k) is a function of , , , , and . High value of VSI(k) means that the voltage at busbar k is not sensitive to the voltage drop from busbar i to k. This means that reduction of and/or does not raise greatly. Reference [7] uses the concept of VSI(k) to get the optimum size and location of the distributed generators. In the present work, this concept has been utilized in getting the optimum capacitor location. This location at busbar i should make VSI(k) minimum. Hence as a general rule in order to get maximum benefit from installing capacitor bank, select or begin with those busbars having least values of VSI.

6. Modified VSI(k), (MVSI(k))

As each busbar has a tolerable range of voltage variation TVR(k):

$$TVR(k)=V_k^{max} - V_k^{min} \quad (6)$$

Where V_k^{max} and V_k^{min} are the maximum and the minimum values of V_Krespectively. Then, it is predicted that the bus with wider TVR can withstand more voltage variation due to capacitor installation with less violations. The present work uses MVSI(k) defined as:

$$\text{MVSI}(k) = \frac{\text{VSI}(k)}{\text{TVR}(k)} \quad (7)$$

This work suggests using MVSI(k) instead of VSI(k) to accelerate the steps of choice.

7. Composite Sensitivity Index (CSI)

CSI is an index which combines the effects of both PLSF and MVSI in on guiding factor to the most appropriate busbar for CB installation. It is calculated as follows for the busbar i:

$$(\text{CSI})_i = \frac{(\text{PLSF})_i}{(\text{MVSI})_i} \quad (8)$$

The factor utilizes the ascending property of and, at the same time the descending property of of the same busbar, thus accelerating the search steps.

8. Steps of Solution

The steps of solution for getting the most favorite bus for capacitors installation which achieve the maximum transmission loss reduction beside avoiding bus voltage violations proceed as follows:

1. Carry out load flow solution to get $P_o^{(0)}$ (source bus power) and $P_i^{(0)}$ and $Q_i^{(0)}$ for all feeder buses before any capacitor installation. The superscript (0) denotes for the results of the first load flow solution.
2. Get the value of $(\text{PLSF})_{Ti}^{(0)}$ and $(\text{MVSI})_{Ti}^{(0)}$ for all feeder buses from equation (4) and (7) respectively.
3. Calculate the value of $(\text{CSI})_i^{(0)}$ for every feeder bus using equation (8).
4. Select the busbar with highest value of $(\text{CSI})_i^{(0)}$ to be the first most favorite busbar for capacitor installation.
5. With the first capacitor has been installed, repeat steps 1-4 to get the second favorite busbar which possesses the maximum value of $(\text{CSI})_i^{(1)}$ for the second load flow solution.
6. Repeat steps 1-5 until all available capacitors are installed.

9. Case Study and Results

The suggested methodology is tested for its effectiveness about search space reduction on the 35-bus distribution system of Figure 2.

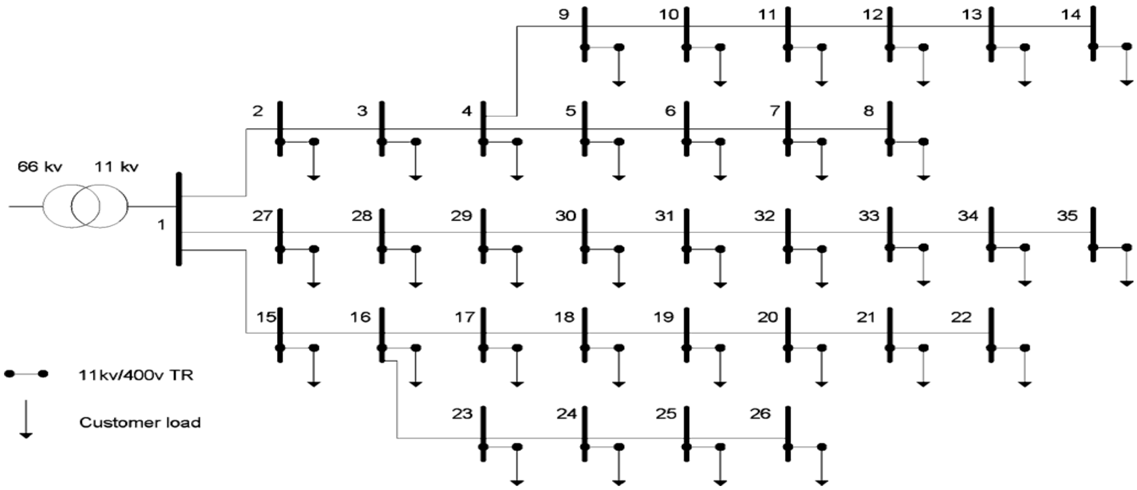

Figure 2– Line diagram of the 35-bus distribution system

The line parameters of the network are cited in Table 1 while the bus loads and bus voltage tolerances are given in Table 2.

Table 1- Line Parameters

Line Section		R (p.u.)	X (p.u.)
Sending end	Receiving end		
1	2	0.009686	0.015187
2	3	0.006954	0.0010904
3	4	0.006209	0.009736
4	5	0.011672	0.018303
5	6	0.011672	0.018303
6	7	0.003229	0.00506
7	8	0.007699	0.012072
4	9	0.003229	0.00506
9	10	0.017136	0.02687
10	11	0.009686	0.015187
11	12	0.006954	0.010904
12	13	0.006209	0.009736
13	14	0.011672	0.018303
1	15	0.040977	0.068543
15	16	0.029802	0.04985
16	17	0.010927	0.018278
17	18	0.023593	0.039464
18	19	0.007947	0.013293
19	20	0.0226	0.037803
20	21	0.00596	0.00997
21	22	0.000993	0.001558
16	23	0.004222	0.00662
23	24	0.006209	0.009736
24	25	0.006954	0.010904
25	26	0.00447	0.00701
1	27	0.009934	0.015577
27	28	0.00298	0.004673
28	29	0.009934	0.0015577
29	30	0.005464	0.008567
30	31	0.011424	0.017913
31	32	0.001987	0.003115
32	33	0.006457	0.010125
33	34	0.00298	0.004673
34	35	0.00298	0.004673

Table 2- Bus Data

Bus	P (kW)	Q(kVAR)	V_{max}	V_{min}
2	19	11.7	1.06	1.04
3	409.1	254.2	1.06	1.04
4	260.9	203	1.06	1.05
5	547.7	243.3	1.06	1.05
6	185.4	153.4	1.06	1.05
7	260.1	146.1	1.06	1.05
8	445.1	157.4	1.06	1.04
9	493.1	203	1.055	1.05
10	186.3	67.7	1.061	1.06
11	342.8	149.3	1.06	1.05
12	319.8	113.1	1.06	1.05
13	68.2	21.9	1.058	1.04
14	244.2	87	1.058	1.04
15	499.4	196.5	1.06	1.05
16	717.5	406.1	1.06	1.045
17	659.5	431.7	1.06	1.05
18	765.6	348.4	1.06	1.04
19	873.5	551.9	1.06	1.05
20	830.6	253	1.058	1.055
21	988	280.5	1.07	1.04
22	346.6	163	1.06	1.04
23	138.8	45.9	1.058	1.04
24	183	41.2	1.057	1.05
25	839.6	190.7	1.058	1.05
26	13.9	4.3	1.06	1.05
27	112.5	14	1.06	1.05
28	86.1	16.2	1.059	1.05
29	774.6	358.1	1.058	1.05
30	461.1	175.8	1.06	1.05
31	242.2	59.5	1.058	1.04
32	48.1	0.1	1.058	1.04
33	348.2	106.7	1.056	1.04
34	0.7	0.8	1.056	1.04
35	394.8	126.6[	1.056	1.04

i. From the first load flow we get:
$P_o^{(0)}$ =13000 kW
$Q_o^{(0)}$ =6000 kvar

And $P_i^{(0)}$ and $Q_i^{(0)}$ for all feeder buses are given in Table 3:

Table 3- $P_i^{(0)}$ and $Q_i^{(0)}$ for all feeder buses before any capacitor installation

Line Section		$P_i^{(0)}$ X 1000 kW	$Q_i^{(0)}$ X 1000 Kvar
Sending end	Receiving end		
1	2	0.001482	0.002324
2	3	0.001054	0.001652
3	4	0.000735	0.001153
4	5	0.000251	0.000393
5	6	0.000095	0.000148
6	7	0.000015	0.000023
7	8	0.000015	0.000024
4	9	0.000091	0.000142
9	10	0.000236	0.00037
10	11	0.000094	0.000148
11	12	0.000028	0.000044
12	13	0.000006	0.00001
13	14	0.000007	0.000011
1	15	0.02	0.03
15	16	0.012848	0.003974
16	17	0.002376	0.003974
17	18	0.00364	0.006088
18	19	0.000778	0.001302
19	20	0.001063	0.001778
20	21	0.000107	0.000179
21	22	0.000001	0.000002
16	23	0.000056	0.000087
23	24	0.000063	0.0001
24	25	0.000048	0.000076
25	26	0	0
1	27	0.000608	0000954
27	28	0.000167	0.000263
28	29	0.000521	0.000816
29	30	0.000121	0.00019
30	31	0.00012	0.000187
31	32	0.000012	0.000019
32	33	0.000036	0.000056
33	34	0.000005	0.000007

The total losses in the system before any capacitor installation is ΣP_1=0.046434 MW.

ii. Bus voltages Vi and values of $(PLSF)_{Ti}^{(0)}$, $(MVSI)_i^{(0)}$and $(CSI)_i^{(0)}$ are given in Table 4. We find that the maximum $(CSI)_i^{(0)}$ occurs at busbar 21 while minimum $(CSI)_i^{(0}$ at busbar 2. Hence according to the proposed method the optimum capacitor location is busbar 21 which corresponds to maximum $(CSI)_i^{(0)}$.

iii. The total losses in the system after installing capacitor bank on the busbar of maximum $(CSI)_i^{(0)}$ is $\Sigma P_{(\text{capacitor bank on BB\#21})}$ =0.045623 MW

The total losses in the system after installing capacitor bank on the busbar of minimum $(CSI)_i^{(0)}$ is

ΣP ($_{\text{capacitor bank on BB\#27}}$) = 0.046353 MW

Table 4- Results of the Case Study

Bus	$(PLSF)_{Ti}^{(0)}$	$(MVSI)_i^{(0)}$	$(CSI)_i^{(0)}$	V_i (p.u)
1				1.0600
2	0.02855	1.26130	0.02263	1.05940
3	0.04286	1.25883	0.03405	1.05897
4	0.04879	1.25755	0.03880	1.05864
5	0.05189	1.25595	0.04132	1.05836
6	0.05237	1.25468	0.04174	1.05819
7	0.05371	1.25388	0.04284	1.05816
8				1.05811
9	0.05092	1.25600	0.04054	1.05855
10	0.05545	1.25556	0.04416	1.05826
11	0.05621	1.25420	0.04482	1.05811
12	0.05634	1.25349	0.04494	1.05805
13	0.05646	1.25321	0.04505	1.05802
14				1.05798
15	1.58840	1.25349	1.26718	1.05545
16	1.80774	1.23971	1.45819	1.05237
17	1.92831	1.22585	1.57304	1.05156
18	1.98406	1.22244	1.62303	1.05011
19	2.00969	1.21587	1.65288	1.04973
20	2.01704	1.21437	1.66098	1.04901
21	2.01707	1.21093	1.66572	1.04890
22				1.04889
23	1.80850	1.22649	1.47453	1.05231
24	1.80935	1.22623	1.47553	1.05222
25	1.80935	1.22582	1.47603	1.05215
26				1.05215
27	0.00465	1.26245	0.00369	1.05964
28	0.04797	1.26074	0.03805	1.05954
29	0.05134	1.26027	0.04074	1.05920
30	0.05316	1.25866	0.04224	1.05908
31	0.05355	1.25808	0.04256	1.05892
32	0.05375	1.25734	0.04275	1.05890
33	0.05383	1.25724	0.04281	1.05883
34	0.05387	1.25691	0.04286	1.05964

According to the obtained results, it is found that the total loss reduction is directly proportional to the value of CSI.

iv. Results of $(CSI)_i^{(1)}$ after installing the capacitor bank on busbar 21 are given in Table 5. The results indicate that the maximum loss reduction occurs when capacitor bank is installed at busbar 21 as has been expected by the proposed method.

Table 5- Results after installing the capacitor bank on busbar 21

Bus	$(\mathbf{PLSF})_{\mathbf{Ti}}^{(\mathbf{1})}$	$(\mathbf{MVSI})_{\mathbf{i}}^{(\mathbf{1})}$	$(\mathbf{CSI})_{\mathbf{i}}^{(\mathbf{1})}$	V_i (p.u)
1				1.04943
2	0.02855	1.26130	0.02263	1.04944
3	0.04286	1.25883	0.03405	1.04953
4	0.04879	1.25755	0.03880	1.05015
5	0.05189	1.25595	0.04132	1.05050
6	0.05237	1.25468	0.04174	1.05185
7	0.05371	1.25388	0.04284	1.05240
8				1.05240
9	0.05092	1.25600	0.04054	1.05248
10	0.05545	1.25556	0.04416	1.05256
11	0.05621	1.25420	0.04482	1.05262
12	0.05634	1.25349	0.04494	1.05559
13	0.05646	1.25321	0.04505	1.05798
14				1.05802
15	1.53930	1.25373	1.22778	1.05805
16	1.74901	1.24042	1.41001	1.05810
17	1.86370	1.22698	1.51894	1.05811
18	1.91621	1.22275	1.56713	1.05815
19	1.94026	1.21769	1.59339	1.05819
20	1.94699	1.21594	1.60122	1.05825
21	1.94720	1.21292	1.60539	1.05836
22				1.05855
23	1.80850	1.22649	1.47453	1.05863
24	1.80935	1.22623	1.47553	1.05880
25	1.80935	1.22582	1.47603	1.05881
26				1.05883
27	0.00465	1.26245	0.00369	1.05890
28	0.04797	1.26074	0.03805	1.05892
29	0.05134	1.26027	0.04074	1.05897
30	0.05316	1.25866	0.04224	1.05908
31	0.05355	1.25808	0.04256	1.05920
32	0.05375	1.25734	0.04275	1.05940
33	0.05383	1.25724	0.04281	1.05954
34	0.05387	1.25691	0.04286	1.05964

10. Conclusions

This paper develops a method for getting the optimal allocation of capacitor banks for transmission loss minimization.

1. The proposed method includes a sensitivity analysis of both transmission loss and voltage profile to capacitor bank installation.
2. By applying the proposed method to a 35-bus system, it has been found that the effect of (PLSF) is much greater than that of (VSI) on the final solution.
3. However, combining these two factors in one integrated factor (CSI) raised the sensitivity of the method and reduced the research space which accelerates the solution time.
4. This may be beneficial in managing capacitor switching scheme coping with load variation.
5. One advantage of the proposed method is that it can be repeated and restarted for getting the second best capacitor bank location just after getting and fixing the first capacitor bank.

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