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Capacitor Placement in Unbalanced Radial Distribution System for Loss Reduction

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Abstract—**Reduction of active power loss in distribution systems is very important to improve the overall efficiency of electrical power distribution systems. The active power loss due to reactive component of branch currents can be reduced by supplying part of the reactive power demands locally with the help of capacitors. This paper proposed a simple method for optimal placement and sizing of capacitor while minimizing power losses and improving the voltage profile in an unbalanced radial distribution system (URDS). The performance of the proposed method have been tested on two case studies 19-bus UBRS and 25-bus UBRS. It was found that a significant loss saving can be achieved by placing optimal capacitors in the system.**

Keywords*— *Load flow; radial distribution systems; capacitor placement

I. INTRODUCTION

A distribution system connects consumers to the high voltage transmission system. The losses in the distribution system are about 5-13% of total generated power. So the loss reduction in the distribution network is the most important priorities in the design and operation of electric power network. There are many ways to reduce the losses as like capacitor placement, Distributed Generation placement, load management, Network Reconfiguration and so on [1].

Several methods for loss reduction on balanced RDS by placing capacitor in an optimal location have been reported in the literature [2-8]. In [9], Decision theory criteria approach was applied to find the optimal allocation and the sizing of capacitors in unbalanced systems with the presence of harmonic sources, also taking into account the uncertainties due to the presence of unbalanced loads. Carpinelli G. et al. [10] proposed a new probabilistic method for the optimal location of capacitors in an unbalanced distribution networks and the micro genetic algorithm was applied to reduce the computational efforts. In [11], a Hybrid Particle Swarm Optimization (HPSO) combined with a Hybrid Power Flow algorithm (HPF) was used to find the optimal locations and sizes of shunt capacitors in an unbalanced RDS while taking the harmonics into account. Carpinelli G. et al. [12] presented a method for placement of shunt capacitors in three phase unbalanced distribution systems with harmonic sources while considering capacitor costs, energy costs as well as costs associated with voltage harmonics. Subrahmanyam JBV, et al. [13] proposed a simple method for choosing optimal location and size of shunt capacitors in three phase unbalanced RDS by taking cost of energy loss and cost related to capacitor purchase and capacitor installation as main objective function to be minimized. The Power Loss Index has been used to select the candidate node for capacitor placement and then variational technique has been used to find the optimal sizes. Based on bacterial foraging oriented by particle swarm optimization algorithm (BFPSO), a new method was proposed to find the optimal location and the size of fixed and switching capacitor banks [14]. In [15], optimal capacitor placement was done by using a hybrid honey bee colony optimization algorithm with the objective function of minimizing power system losses and unbalances and maximizing the net savings while maintaining voltage and total harmonic distortion of buses in an acceptable. The Index Vector method was implemented for optimal capacitor placement on three phase unbalanced radial distribution system [16]. Haque M.H. proposed loss reduction technique in balanced radial distribution system by supplying the reactive power locally with the help of capacitors [7]. However, this paper proposes single capacitor placement method for loss reduction in an unbalanced radial distribution system. The basic idea of the proposed method has been taken from [7]. In this proposed method, the optimal size of capacitor at each node can be determined through optimizing the loss saving equation. The node at which the loss saving is maximum will be taken as candidate node for capacitor placement and the corresponding size is the optimal size of capacitor. The load flow of unbalanced radial distribution has been implemented from [17]. The results have been obtained for unbalanced distribution network of IEEE 19 bus and IEEE 25 bus systems [18].

II. PROPOSED LOAD FLOW APPROACH IN DISTRIBUTION SYSTEMS

Let us consider the following
$Ploss$ = Total real power loss.
$Qloss$ = Total reactive power loss.
$Sloss = Ploss + j\, Qloss$
I_a, I_b, I_c are the branch currents in three phases.
I_{ar}, I_{br}, I_{cr} are the active component of branch currents in three phases.
I_{ai}, I_{bi}, I_{ci} are the reactive component of branch currents in three phases.
Z is the branch impedance.

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α is the set of branches from source bus to the jth capacitor bus.

The total power loss in an unbalanced distribution system is given by [19]

$$Sloss = \sum_{branches} Z_{aa} * I_a * (I_a)^* + Z_{ab} * I_b * (I_a)^* + Z_{ac} * I_c * (I_a)^* + Z_{ba} * I_a * (I_b)^* + Z_{bb} * I_b * (I_b)^* + Z_{bc} * I_c * (I_b)^* + Z_{ca} * I_a * (I_c)^* + Z_{cb} * I_b * (I_c)^* + Z_{cc} * I_c * (I_c)^* \quad (1)$$

Where $I_a = I_{ar} + jI_{ai}$

$$I_b = (I_{br} + jI_{bi}) * \left(-\frac{1}{2} - j\frac{\sqrt{3}}{2}\right)$$

$$I_c = (I_{cr} + jI_{ci}) * \left(-\frac{1}{2} + j\frac{\sqrt{3}}{2}\right)$$

$$Sloss = Ploss + j\,Qloss$$

$Ploss$ associated with both active and reactive component of branch currents can be given as:

$$Ploss = \sum_{branches} R_{aa} * (I_{ar}^2 + I_{ai}^2) + R_{bb} * (I_{br}^2 + I_{bi}^2) + R_{cc} * (I_{cr}^2 + I_{ci}^2) + R_{ab}\left(-I_{ar}I_{br} - I_{ai}I_{bi} + \sqrt{3}I_{ar}I_{bi} - \sqrt{3}I_{ai}I_{br}\right) + R_{bc}\left(-I_{br}I_{cr} - I_{bi}I_{ci} + \sqrt{3}I_{br}I_{ci} - \sqrt{3}I_{bi}I_{cr}\right) + R_{ca}\left(-I_{cr}I_{ar} - I_{ci}I_{ai} + \sqrt{3}I_{cr}I_{ai} - \sqrt{3}I_{ci}I_{ar}\right) \quad (2)$$

For a given configuration of single source unbalanced radial network, $Ploss$ associated with active component of branch current cannot be minimized because all active power must be supplied by the source at the root bus. However, the $Ploss$ associated with the reactive component of branch currents can be minimized by supplying part of the reactive power demands locally. [7]

Ploss associated with reactive component of current is

$$Ploss_r = \sum_{branches} R_{aa} * I_{ai}^2 + R_{bb} * I_{bi}^2 + R_{cc} * I_{ci}^2 + R_{ab} * \left(-I_{ai}I_{bi} + \sqrt{3}I_{ar}I_{bi} - \sqrt{3}I_{ai}I_{br}\right) + R_{bc} * \left(-I_{bi}I_{ci} + \sqrt{3}I_{br}I_{ci} - \sqrt{3}I_{bi}I_{cr}\right) + R_{ca} * \left(-I_{ci}I_{ai} + \sqrt{3}I_{cr}I_{ai} - \sqrt{3}I_{ci}I_{ar}\right) \quad (3)$$

After placing the capacitor at a particular node, it draws a reactive current IC. The reactive component of branch currents will be affected in the branch set ∝. The current of other branches (∉∝) is unaffected by the capacitor. The single line diagram of 19 bus unbalanced distribution system is shown in Figure 1. If the capacitor is placed at bus 7, then the set ∝ consist of 1,3,5 and 6 branches.

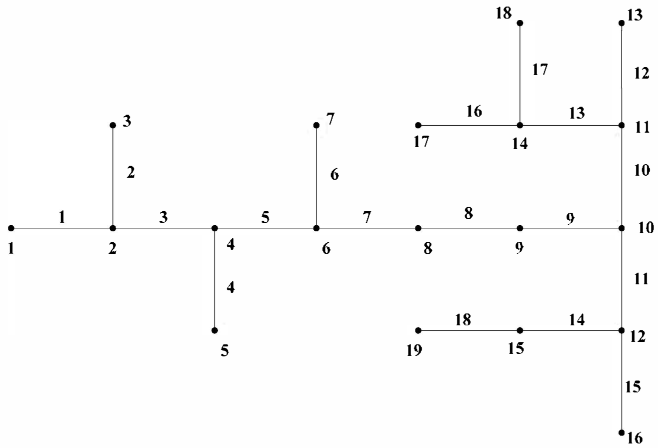

Fig. 1. Single line diagram of 19 bus unbalanced RDS

After placing the capacitor, the new branch currents in three phases are given by

$$I_{ai(new)} = I_{ai} + D * IC_a$$
$$I_{bi(new)} = I_{bi} + D * IC_b$$
$$I_{ci(new)} = I_{ci} + D * IC_c$$

Where D=1 ; if branch ∈ ∝
=0 ; otherwise

After capacitor placement, the $Ploss$ for the compensated system can be written as

$$Ploss_r^{cap} = \sum_{branches} R_{aa} * (I_{ai} + D * IC_a)^2 + R_{bb} * (I_{bi} + D * IC_b)^2 + R_{cc} * (I_{ci} + D * IC_c)^2 + R_{ab}\left(-(I_{ai} + D * IC_a)(I_{bi} + D * IC_b) + \sqrt{3}I_{ar}(I_{bi} + D * IC_b) - \sqrt{3}I_{br}(I_{ai} + D * IC_a)\right) + R_{bc}\left(-(I_{bi} + D * IC_b)(I_{ci} + D * IC_c) + \sqrt{3}I_{br}(I_{ci} + D * IC_c) - \sqrt{3}I_{cr}(I_{bi} + D * IC_b)\right) + R_{ca}\left(-(I_{ci} + D * IC_c)(I_{ai} + D * IC_a) + \sqrt{3}I_{cr}(I_{ai} + D * IC_a) - \sqrt{3}I_{ar}(I_{ci} + D * IC_c)\right) \quad (4)$$

The loss saving $Ploss_{saving}$ is the difference between eqn ()-() and is given by

$$Ploss_{saving} = Ploss_r - Ploss_r^{cap} \quad (5)$$

$$Ploss_{saving} = \sum_{branches} R_{aa} * \left(D * {IC_a}^2 + D * 2I_{ai} * IC_a\right) + R_{bb} * \left(D * {IC_b}^2 + D * 2I_{bi} * IC_b\right) + R_{cc} * \left(D * {IC_c}^2 + D * 2I_{ci} * IC_c\right) + R_{ab}\left[-(D * I_{ai} * IC_b + D * I_{bi} * IC_a + D * IC_a * IC_b) + D * \sqrt{3}I_{ar} * IC_b - D * \sqrt{3}I_{br} * IC_a\right] + R_{bc}\left[-(D * I_{bi} * IC_c + D * I_{ci} * IC_b + D * IC_b * IC_c) + D * \sqrt{3}I_{br} * IC_c - D * \sqrt{3}I_{cr} * IC_b\right] + R_{ca}\left[-(D * I_{ci} * IC_a + D * I_{ai} * IC_c + D * IC_a * IC_c) + D * \sqrt{3}I_{cr} * IC_a - D * \sqrt{3}I_{ar} * IC_c\right] \quad (6)$$

The capacitor current IC that provides the maximum loss saving can be obtained by differentiating the equation () and is given by

$$\frac{\partial Ploss_{saving}}{\partial IC_a} = \sum_{branches} R_{aa} * (D * 2IC_a + D * 2I_{ai}) + R_{ab} * \left[-(D * I_{bi} + D * IC_b) - D * \sqrt{3}I_{br}\right] + R_{ac} * \left[-(D * I_{ci} + D * IC_c) + D * \sqrt{3}I_{cr}\right] = 0 \quad (7)$$

$$\frac{\partial Ploss_{saving}}{\partial IC_b} = \sum_{branches} R_{bb} * (D * 2IC_b + D * 2I_{bi}) + R_{ba} * \left[-(D * I_{ai} + D * IC_a) + D * \sqrt{3}I_{ar}\right] + R_{bc} * \left[-(D * I_{ci} + D * IC_c) - D * \sqrt{3}I_{cr}\right] = 0 \quad (8)$$

$$\frac{\partial Ploss_{saving}}{\partial IC_c} = \sum_{branches} R_{cc} * (D * 2IC_c + D * 2I_{ci}) + R_{cb} * \left[-(D * I_{bi} + D * IC_b) + D * \sqrt{3}I_{br}\right] + R_{ca} * \left[-(D * I_{ai} + D * IC_a) - D * \sqrt{3}I_{ar}\right] = 0 \quad (9)$$

Arranging the equations (-) in matrix form,

The capacitor currents for maximum loss savings cab be calculated as

$$\begin{bmatrix} IC_a \\ IC_b \\ IC_c \end{bmatrix} = [MATRIX1]^{-1} * [MATRIX2] \quad (10)$$

$$MATRIX1 = \sum_{j \in \alpha} \begin{bmatrix} 2R_{aa}(j) & -R_{ab}(j) & -R_{ac}(j) \\ -R_{ba}(j) & 2R_{bb}(j) & -R_{bc}(j) \\ -R_{ca}(j) & -R_{cb}(j) & 2R_{cc}(j) \end{bmatrix}$$

Here α is the set of branches from source bus to the jth capacitor bus.

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$$MATRIX2 = \sum_{j\in\alpha} \begin{bmatrix} \sqrt{3}R_{ab}(j) * I_{br}(j) - \sqrt{3}R_{ac}(j) * I_{cr}(j) - 2R_{aa}(j) * I_{ai}(j) + R_{ab}(j) * I_{bi}(j) + R_{ac}(j) * I_{ci}(j) \\ -\sqrt{3}R_{ba}(j) * I_{ar}(j) + \sqrt{3}R_{bc}(j) * I_{cr}(j) + R_{ba}(j) * I_{ai}(j) - 2R_{bb}(j) * I_{bi}(j) + R_{bc}(j) * I_{ci}(j) \\ \sqrt{3}R_{ca}(j) * I_{ar}(j) - \sqrt{3}R_{cb}(j) * I_{br}(j) + R_{ca}(j) * I_{ai}(j) + R_{cb}(j) * I_{bi}(j) - 2R_{cc}(j) * I_{ci}(j) \end{bmatrix}$$

The corresponding capacitor size is,

$$QC_a = IC_a * V_{am} \tag{11}$$

$$QC_b = QC_c = QC_a \tag{12}$$

Here V_{am} is the voltage magnitude of phase-A at capacitor bus. The above procedure can be repeated for all nodes to get the highest possible loss saving for a single capacitor placement and the node at which loss savings are maximum will be considered as candidate node for capacitor placement and the corresponding size (A phase only) is the optimal size of capacitor.

Algorithm:

Step 1. Run the base case load flow and obtain the branch currents.

Step 2. Select a bus and then find the maximum loss saving using equation (6) and the corresponding size by using equation (11).

Step 3. Repeat step 2 for all buses except at source bus and identify the bus at which the loss saving is highest.

Step 4. Compensate the selected bus with the corresponding capacitor size.

III. RESULTS AND DISCUSSIONS

A. *Case study 1: 19-bus URDS*

The load flow of unbalanced radial distribution system has been implemented from [17]. The proposed algorithm is tested on an 11-kV, 19-bus URDS. The line and load data are obtained from [18]. The base load of the system in a-phase, b-phase, c-phase are 126.33+j*61.23 kVA, 116.34+j*56.339 kVA, 123.27+j*59.7 kVA respectively. Highest loss savings obtained at bus 10 with corresponding size of 23.1517 kVAr in each phase. The total active power losses reduced from 13.4709 kW to 11.5281 kW, total reactive power losses reduced from 5.7956 kVAr to 4.9597 kVAr and the minimum voltages in phases a, b, and c are improved from 0.9515, 0.9494, and 0.9504 p.u. to 0.9560, 0.9542, and 0.9549 p.u. after installing the capacitor banks. The voltage, the total active loss (TPL) and reactive power loss (TQL), minimum voltages for the 19-bus URDS before and after compensation are given in Table 1..

B. *Case study 2: IEEE 25-bus URDS*

The proposed algorithm is also tested on a 4.16-kV, 25-bus URDS shown in Fig. 2. The line and load data are obtained from [18]. The base load of the system in phases a, b, and c are 1073.3+j*792 kVA, 1083.3+j*800 kVA, 1083.3+j*800 kVA respectively. Highest loss savings obtained at bus 7 with corresponding size of 484.773kVAR in each phase. The total active power losses reduced from 150.11795kW to 109.6207kW, total reactive power losses reduced from 167.27536kVAR to 121.4229kVAR and the minimum voltages in phases a, b, and c are improved from 0.9284, 0.9283, and 0.9365 p.u. to 0.9505, 0.9484, and 0.9573 p.u. after installing the capacitor banks. The voltage, the total active power loss (TPL) and reactive power loss(TQL), minimum voltages for the 25-bus URDS before and after compensation are given in TableII.

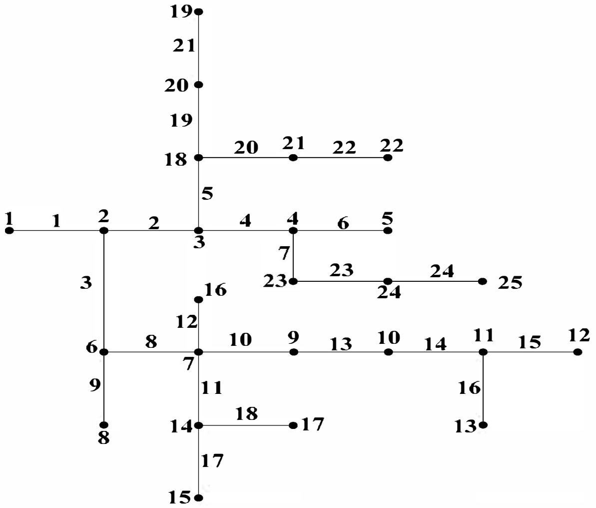

Fig. 2. Single line diagram of 25 bus unbalanced RDS.

Table I. IEEE19 bus unbalanced radial system

Node	Before Capacitor Placement			After Capacitor Placement		
	Va (p.u)	Vb (p.u)	Vc (p.u)	Va (p.u)	Vb (p.u)	Vc (p.u)
1	1	1	1	1	1	1
2	0.98746	0.98910	0.98798	0.98829	0.98994	0.98881
3	0.98542	0.98869	0.98633	0.98625	0.98952	0.98717
4	0.98235	0.98390	0.98301	0.98360	0.98515	0.98425
5	0.98201	0.98366	0.98283	0.98325	0.98491	0.98408
6	0.97928	0.98078	0.98005	0.9808	0.98231	0.98158
7	0.97861	0.98029	0.97957	0.98013	0.98182	0.98109
8	0.97282	0.97382	0.97347	0.97502	0.97604	0.97569
9	0.96592	0.96598	0.96575	0.96895	0.96903	0.96880
10	0.95626	0.95549	0.95501	0.96067	0.95993	0.95944
11	0.95499	0.95430	0.95331	0.95942	0.95874	0.95774
12	0.95478	0.95377	0.95358	0.95920	0.95822	0.95802
13	0.9544	0.95344	0.95211	0.95882	0.95788	0.95655
14	0.95449	0.95388	0.95283	0.95891	0.95833	0.95727

15	0.95275	0.95122	0.95126	0.95718	0.95568	0.95571
16	0.95339	0.95148	0.95218	0.95782	0.95593	0.95662
17	0.95366	0.95337	0.95232	0.95808	0.95782	0.95677
18	0.95380	0.95319	0.95209	0.95822	0.95764	0.95654
19	0.95160	0.94976	0.95047	0.95603	0.95423	0.95492
Min V	0.95160	0.94976	0.95047	0.95603	0.95423	0.95492
Capacitor Size (kVAr)	-	-	-	23.1517	23.1517	23.1517
location				10		
Active power loss (kW)	4.4539	4.4532	4.5637	3.8179	3.7969	3.9133
Active power loss reduction (%)	-	-	-	14.279	14.738	14.252
Reactive power loss (kVAr)	1.9405	1.8964	1.9587	1.6724	1.6165	1.6708
Reactive power loss reduction (%)	-	-	-	13.816	14.76	14.70
TPL (kW)	13.4709			11.5281		
TQL (kVAr)	5.79562			4.9597		

Table II. Results for IEEE 25 bus unbalanced radial system

Node	Before Capacitor Placement			After Capacitor Placement		
	Va (p.u)	Vb (p.u)	Vc (p.u)	Va (p.u)	Vb (p.u)	Vc (p.u)
1	1	1	1	1	1	1
2	0.97020	0.9711	0.97545	0.97958	0.97939	0.98418
3	0.96323	0.96444	0.96984	0.97267	0.97278	0.97862
4	0.95978	0.96129	0.96739	0.96926	0.96965	0.97619
5	0.95872	0.96025	0.96644	0.96821	0.96862	0.97525
6	0.95498	0.95587	0.96148	0.97056	0.96987	0.97606
7	0.94191	0.94283	0.94923	0.96373	0.96256	0.96971
8	0.95286	0.95379	0.95957	0.96847	0.96781	0.97418
9	0.93589	0.93668	0.94379	0.95785	0.95654	0.96439
10	0.93150	0.93186	0.93953	0.95356	0.95182	0.96022
11	0.92941	0.92963	0.93763	0.95153	0.94963	0.95836
12	0.92841	0.92840	0.93660	0.95055	0.94842	0.95735
13	0.92871	0.92872	0.93682	0.95084	0.94874	0.95757
14	0.93594	0.93699	0.94338	0.95790	0.95685	0.96399
15	0.93377	0.93487	0.94144	0.95578	0.95476	0.96209
16	0.94083	0.94177	0.94826	0.96268	0.96153	0.96876
17	0.93473	0.93595	0.94203	0.95672	0.95582	0.96267
18	0.95732	0.95864	0.96432	0.96682	0.96702	0.97315
19	0.95241	0.95443	0.95998	0.96196	0.96285	0.96885
20	0.95482	0.95634	0.96201	0.96435	0.96475	0.97087
21	0.95379	0.95487	0.96053	0.96333	0.96328	0.9694
22	0.95184	0.95246	0.95852	0.9614	0.96090	0.96740
23	0.95647	0.95838	0.96479	0.96598	0.96677	0.97361
24	0.95444	0.95651	0.96311	0.96397	0.96492	0.97195
25	0.95202	0.95469	0.96117	0.96158	0.96311	0.97003
Min V	0.92841	0.92840	0.93660	0.95055	0.94842	0.95735
Capacitor Size (kVAr)	-	-	-	484.773	484.773	484.773
location				7		
Active power loss (kW)	52.8133	55.4431	41.8615	38.6027	40.4463	30.5715
Active power loss reduction (%)	-	-	-	26.907	27.049	26.969
Reactive power loss	58.2902	53.2941	55.6911	42.3424	38.6939	40.3866

(kVAr)						
Reactive power loss reduction (%)	-	-	-	27.359	27.396	27.481
TPL (kW)	150.11795			109.6207		
TQL (kVAr)	167.27536			121.4229		

IV. CONCLUSIONS

A simple method for optimal placement and sizing of capacitor while minimizing power losses and improving the voltage profile in an unbalanced radial distribution system has been presented in this paper. The method first finds the possible loss savings by placing optimal capacitor size in each phase at every node (except source node). The node at which the loss savings are maximum will be taken as candidate node and the corresponding capacitor size is the optimal size. Proposed method has been implemented on two case studies i.e IEEE 19-bus UBRS and IEEE 25-UBRS. The result shows that with the help of single capacitor placement in an unbalanced radial distribution system, the voltage profile has been improved and the burden on the substation has been reduced due to reduction in losses.

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