Cost–Benefit Analysis in Distribution System of Jaipur City After DG and Capacitor Allocation

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Abstract Distributed generation (DG) and shunt capacitors are widely adopted for minimizing power loss in distributed networks. But the high cost of DG units puts a limitation on employing higher rating DGs in distribution networks. So, it is desired that less DG size gives maximum loss reduction for achieving the objective of minimum overall cost of the system. The prominent goal of this paper is to curb the total expenditure occurring due to annual energy loss and cost incurred in installing DG units and capacitor banks. An unsullied methodical approach has been presented in this paper to find out optimal position and rating of DG as well as capacitor units so that the overall cost would be minimal. The method is tested on standard IEEE 69 bus distribution system and 130 bus Indian distribution systems. The outcomes of both the test systems are optimistic and found to be promising when compared with the previous ones.

Keywords Real power loss (RPL) · Capacitor units · Distributed generation (DG) · Radial distribution system (RDS)

1 Introduction

Distributed generation (DG) is used for pollution-free electric power production. The connotation of distributed generation refers to the small generating units which are installed in the neighborhood of the load side in order to avoid the future expansion requirements. The DGs are installed in the system to primarily reduce active power loss which in turn leads to diminution of energy loss with enhancement of voltage profile. The renewable-based DG units (solar PV, windmills, etc.) are generally used for power generation. But the cost of such types of DGs is very high. In India, the cost of 10 kW on a grid solar power plant is around Rs. 5 lacs. It is desirable to

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determine the best position and rating of DG units for minimizing the overall cost of the system.

Numerous researchers proposed various optimization techniques in order to determine the site and size of the DG units in RDS. Authors formulated analytical expressions for optimal allocation of DG at different loading conditions in RDS to minimize the RPL [1].

Abou El-Ela [2] presented a genetic algorithm for DG allocation in order to increase spinning reserve, enhancement in bus voltages, and to reduce transmission loss.

In [3], a new expression has been investigated for determining the optimal size of DGs for dropping RPL in distribution systems. Barker [4] explained various aspects (like voltage profile, RPL, and distribution capacity and power quality issues) of DG placement in RDS. Aman et al. proposed [5] a step-by-step iterative algorithm to find the best location of the DG units. An improved loss-sensitivity analysis method is proposed to identify and locate optimal DG units in a radial distribution system in [6]. The significant improvement is observed in percentage loss reduction and voltage profile. Rueda-Medina [7] proposed a mixed-integer linear programming technique in RDS for locating DG units of optimal size. Koutroulis et al. [8] presented cost–benefit analysis of DG allocation in RDS while considering renewable-based DG units individually. The main objective is to minimize the total system cost. In [9], authors proposed CPF algorithm and incorporated modal analysis to solve DG's allocation problem in RDS.

This paper presents a new-fangled technique to place DG and capacitor units with optimal sizing. The total expenditure, occurring due to annual energy loss and installation of DG and capacitor bank, has been reduced in the paper. A new and simple mathematical expression, PSC, is formulated which incorporates power loss and voltage profile. The PSC yields optimal size and position of DG and capacitor units separately. The above methodology is tested on two test systems, i.e., IEEE 69 bus system and 130 bus rural system of Jaipur city. The results obtained for both test systems are optimistic and encouraging.

2 Problem Formulation

This paper intends to minimize the total expenditure occurring due to annual energy loss and installation of DG and capacitor bank with gratifying constraints.

The problem can be expressed mathematically as follows:

Minimize F = Cost due to energy loss + Cost of capacitor installation + Cost of DG installation

$$\text{Min. f} = K_{\text{E}} * P_{\text{loss}} * t + K_{\text{C}} * T_{\text{C}} + K_{\text{D}} * T_{\text{DG}} \tag{1}$$

Operating constraints are

(i) Power balancing constraints.
(ii) Total size of DG units $\leq 0.5 * P_{\text{Load.}}$
(iii) Voltage constraints $0.95 \leq V_{\text{m}} \leq 1.0$.
(iv) The injected reactive power should exceed the total system reactive power demand.

where

K_{E} per unit energy cost;
P_{loss} sum of active power loss of the network (kW);
T 8760 h;
K_{C} Cost of per kVAr capacitor unit including installation;
T_{C} Total rating of capacitor bank in kVAr;
K_{D} Cost of per kW DG unit including installation;
T_{DG} Total rating of DG units in kW; and
P_{load} Real power load of system (kW).

As per the Jaipur city scenario, the most favorable renewable-based DG unit is the solar power plant. The cost of all constants has been taken as specified in Rajasthan state.

$K_{\text{E}} =$ Rs. 5 per unit,
$K\text{c} =$ Rs. 225 per kVAr, and
$K_{\text{D}} =$ Rs. 50,000 per kW.

3 Proposed Technique

A new method is anticipated for placing capacitor and DG units separately. PSC calculates the optimal size and location of DG and capacitor units such that the total expenditure should is minimum.

$$\text{PSC} = \frac{V_{\text{rated}}}{V_{\text{m}}} + \frac{P_{\text{dgloss}}}{P_{\text{realloss}}} \tag{2}$$

P_{realloss} Real power loss for base case (kW).
P_{dgloss} Power loss after placement of DG/capacitor units at the ith bus (kW).
V_{m} Minimum bus voltage.

The value of P_{dgloss} should be lowest and V_{min} should be highest for the best allotment of DG units. Hence, “PSC” should be the smallest. The process to solve the problem is explained in [10].

4 Results

To test the efficacy of the proposed methodology, two test systems, real distribution system of 130 bus Jaipur city and IEEE standard bus system of 69 bus are incorporated.

4.1 69 Bus Test System

The IEEE 69 bus system has 12.66 kV and 100 MVA base values [11]. The total active and reactive system load is 3802 kW and 2694 kVAr, respectively. The active power losses for the base case are 225 kW and the minimum voltage is 0.9092 pu. Three different cases are considered for placing DG and capacitor units.

I: DGs placement,
II: Capacitors placement, and
III: Combination of DGs and capacitors placement.

Case I: Only DGs placement
In Case I, only DG units are placed in IEEE 69 bus standard system.

The result of DG allocation has been presented in Table 1. DG units of size 330 kW, 920 kW, and 560 kW are placed at location 21, 61, and 64, respectively. The RPL of the system is decreased to 76.7 kW from 225 kW.

Case II: Only capacitor placement
Similarly, the best position and rating of capacitors are determined by the proposed technique. The proposed methodology yields three different positions with the finest rating being obtained as 750 kVAr (bus no. 61), 270 kVAr (21), and 400 kVAr (64). After installation of the aforesaid capacitors, size, and its required location, a reduction of 78 kW is observed from the base case. The minimum voltage is also improved to 0.93 pu from 0.909 as shown in Table 2.

Case III: Combination of DGs and capacitors placement
In this case, both DG and capacitors are placed simultaneously. Table 3 exhibits the results of Case III. It is pragmatic that there is a significant reduction in real power loss reduction that accounts for 94.8%. The total cost is calculated as 918.32

Table 1 Results of 69 bus systems

	Without DG	With DG
Power loss (kW)	225	76.8
DG rating in kW (bus no.)	–	330 (21) 920 (61) 560 (64)
Total DG rating in kW	–	1810
% loss reduction	–	65.75
$V_{\min}$ (pu)	0.909	0.970

Table 2 Outcome of IEEE 69 bus system (before and after capacitor placement)

	Before capacitor placement	After capacitor placement
Power loss (kW)	225	147
Capacitor size in kVAr (bus no.)	–	750 (61) 270 (21) 400 (64)
Total capacitor size in kW	–	1420
% loss reduction	–	34.66
V_{min} (pu)	0.909	0.93

Table 3 Summarized results of 69 bus system for Case III

DG rating in kW	Capacitor rating in kVAR	$P_{realLoss}$ in kW	V_{min} (p.u.)	% loss reduction (from base case)	Total cost in Lacs/year (f)
1810	1420	11.7	0.99	94.8%	918.32

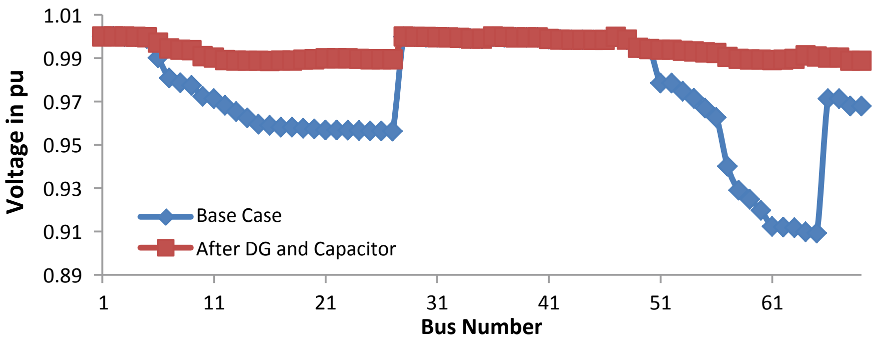

Fig. 1 Voltage profile of IEEE 69 bus system for Case III

lacs/annum. V_{min} is also improved from 0.90 to 0.99 pu after placing a capacitor and DG units simultaneously.

Figure 1 showcases the voltage contour for the base case and after placement of compensation elements.

Table 4 exhibits the comparison of results of the proposed technique with the latest techniques such as MINLP [12], IMDE [13], and EA [14] which are proposed in the topical past. In the proposed approach, the overall expenditure of the system is less than the other ones. In other techniques, the size of the DG is very high. It is noteworthy to notice that after 50% DG penetration, the power loss reduction is very slow. As a result, it will only increase the installation cost of DG units but the cost reduction due to energy loss is awfully less. The improved bus voltage profile is also shown in Fig. 1.

Table 4 Assessment of results for 69 bus system for Case III

	MINLP [12]	IMDE [13]	Evolutionary algorithm [14]	Proposed
DG size in kW	2547	2217	2549	1810
Capacitor size in kVAr	1806	2282	1801	1420
Real power loss	4.27	13.83	4.25	11.7
% Loss reduction	98.10	93.84	98	94.8
V_{min}	0.99	0.99	0.99	0.99
Total annual cost in INR Lacs for first year only (f)	1279	1119.7	1280.4	918.32

4.2 130 Bus (Jaipur City) System

The proposed technique is also examined on a real system of 130 bus Jaipur city. The total active and reactive load of the system accounts for 1.878 MW and 1.415 MVAr, respectively. The base value of the system is 11 kV and 100 MVA [10]. The real power losses for the base case are 330 kW and V_{min} is 0.83 pu. The proposed technique is also addressed on the 130 bus real distribution system of Jaipur rural area. The first five candidate buses are identified for placing of DG and capacitors units. Table 5 presents the result of 130 bus system after DG and capacitor installation.

Table 5 exhibits consolidated results of 130 bus radial distribution system. It is observed that losses are reduced to 141.6, 209, and 44 kW after placement of DG unit (Case I), after placement of capacitor unit (Case II), and after placement of

Table 5 Summary of results of 130 bus system for Case I, II, and III

Item	Without any compensation	After placement of DG unit only	After capacitor placement only	Combined placement of DG and capacitor
Total loss	330	141.6	209	44
% Loss reduction	–	57.7%	38%	87%
V_{min} in pu	0.83	0.9161	0.872	0.95
Optimal rating (location) in kW/kVAr	–	220 (106) 120 (115) 140 (119) 180 (122) 290 (128)	280 (53) 150 (77) 140 (114) 160 (120) 200 (126)	
Total kW/kVAr	–	940	930	940+j930
Total cost (f) in INR. Lacs/year	146.73	532.02	93.20	491.36

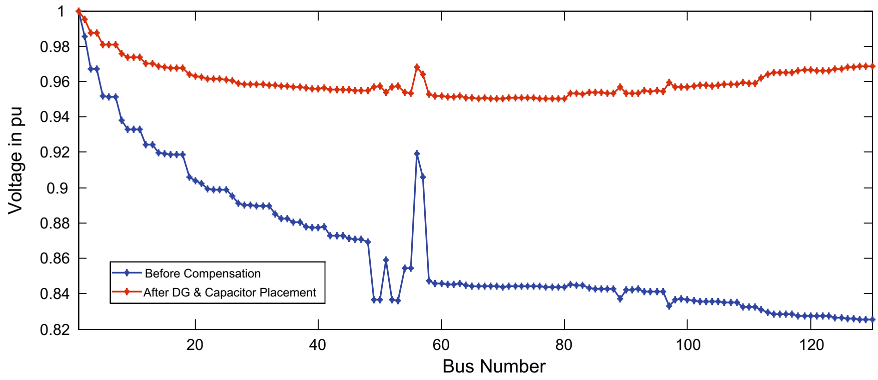

Fig. 2 Voltage profile for 130 bus system

both, DG and capacitor units. Analogously the percentage loss reduction accounts for 57.7, 38, and 87% for the aforesaid three cases. The $V_{\min}$ is also enhanced from 0.83 to 0.95 pu after DG and capacitor installation. Initially (when there are no compensation devices), the expenditure of energy loss is 146.73 Lacs/year. This will reduce to 19.27 lacs/year after compensation. The installation cost of solar-based DG and capacitor would be 470 lacs and 2.09 lacs, respectively. The total cost (f) after DG and capacitor placement would be INR 491.36 Lacs for the first year of installation. After that, it would be only INR 19.27 Lacs for the upcoming years. The enhanced voltage summary after allocations is shown in Fig. 2.

5 Conclusion

In this paper, an efficient and robust technique is investigated to determine the best size and location of DG and capacitor units in a distribution system. This in return will reduce the overall cost of the system. The overall cost includes energy loss cost, installation cost of solar-based DG unit and capacitor bank. A new and simple mathematical term, Power sensitivity constant (PSC), is formulated. The PSC determines the best location and rating of the DG and capacitors. The aforesaid method is applied on standard 69-bus and 130-bus system. The comparison of the results with the latest methods shows the efficacy of the proposed approach. The results of the real system are also promising. It will be concluded that there will be a huge saving in running expenses after DG and capacitor installation by the proposed technique. The results of the real system have also been confirmed by Rajasthan Vidyut Vitran Nigam Ltd. (RVVNL), Jaipur.

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