Optimal Placement and Sizing of Capacitor and Distributed Generator in Radial Distribution System

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ABSTRACT

Distribution Systems are growing large and being stretched too far, leading to higher system losses and poor voltage regulation, the need for an efficient and effective distribution system has therefore become more urgent and important. A distribution system connects consumers to the high-voltage transmission system. Because of lower voltage, and hence higher current, the I²R loss in a distribution system is significantly high compared to that in a high-voltage transmission system. The pressure of improving the overall efficiency of power delivery has forced the power utilities to reduce the loss, especially at the distribution level. Loss reduction initiatives in distribution systems have been activated due to the increasing cost of supplying electricity, the shortage in fuel with ever-increasing cost to produce more power, and the global warming concerns. The total system loss can be decreased by installing capacitor bank and distributed generation. These two methods can also help maintaining the level of voltage and maintenance power factor. The direct search algorithm is applied to minimize the loss in radial distribution systems.

KEYWORDS: *Capacitor, Distributed Generator, Optimal Location, Radial Distribution*

I. INTRODUCTION

Distribution system constitutes the link between electricity utilities and consumers and their revenue realization segment. For consumers, it represents the face of the utility. The modern distribution system begins as the primary circuit leaves the sub-station and ends as the secondary service enters the customer's meter socket by way of service main. Distribution circuits serve many types of customers. The voltage used is appropriate for the shorter distance and varies from 230 to about 33,000 volts depending on utility standard practice, distance, and load to be served. Distribution circuits are fed from a transformer located in an electrical substation, where the voltage is reduced from the high values used for power transmission.

II. LOAD FLOW SOLUTION

Traditional transmission system load flow methods Gauss-Siedel and Newton Raphson techniques cannot be used for distribution systems as R/X ratio is high. Network-Topology-Based Three-Phase Load Flow for Distribution Systems is used in this dissertation work.

The capacitor placement problem consists of determining the optimal numbers, locations and sizes of capacitor such that minimum yearly cost due to power/energy losses and cost of capacitors is achieved. In this dissertation work, optimal sizes of the switched capacitors in terms of standard sizes available in the market and their locations are to be determined for maximum possible reduction in the loss for radial distribution system. Standard capacitor sizes available in the literature (in KVAR): 150, 300, 450, 600, 750, 900, 1050, 1200, 1350, 1500, 1650, 1800, 1950, 2100, 2250, 2400, 2550, 2700, 2850, 3000, 3150, 3300, 3450, 3600, 3750, 3900, 4050.

III. SOLUTION METHODOLOGY

In this dissertation work, Direct Search Algorithm is used to determine the optimal sizes of switched capacitors together with their optimal locations in radial distribution systems so that maximum possible reduction in losses is achieved. The algorithm is used for radial distribution system

with source bus as slack bus and all other load buses as PQ buses. The algorithm is described in following steps for deciding the optimal sizes of the capacitors in terms of standard sizes available in the market and their locations (only load buses).

1. Read the system data of the distribution system. Run Base case load flow and determine the total active power loss (P_{loss}) of the system.

2. Make Q_{load} =0 by fully compensating all load buses. Run the load flow. Determine $P_{loss.}$ (This is the minimum possible loss of the system to be aimed at for determining optimal sizes and locations of Capacitors.)

3. Make 'n' number of capacitors of different sizes, whose total is equal to or near $Q_{total.}$ Let m(k) be the number of capacitor where k is ranging from 1 to n.

4. Place first capacitor at each load bus in turn and determine P_{loss} in each case. Identify the location where system loss is minimum ($P_{loss(min)}$) Repeat this procedure for other sizes of capacitors. Now determine the minimum of $P_{loss(min)}$ and place the corresponding optimal capacitor at the corresponding optimal location.

5. Repeat Step-4 for optimal placement of remaining capacitors till minimum possible loss is achieved i.e. further placement of capacitor will result in increase in the loss.

The sizing and sequencing of capacitors depend on load pattern and can be adjudged by the expert analyst.

IV. OPTIMAL DISTRIBUTED GENERATOR PLACEMENT FOR LOSS REDUCTION

The share of distributed generators (DGs) in power systems has been slowly increasing in the last few years. DG placement can cause reduction of power losses and improvement of voltage profile. There are many reasons for using DG units such as reduction of system harmonics, improvement of power quality, improvement of reliability of systems, improvement of voltage profile and avoiding of investment in infrastructure of distribution and transmission networks. Distributed Generators can be divided into four types, namely

a) Type-1 DG: It injects both real and reactive power into the system. Power factor (PF_{DG}) of the DG is $0 < PF_{DG} < 1$. Synchronous Generator is an example of Type-1 DG.

b) Type-2 DG: It is capable of injecting real power but consumes reactive power from the system. Power factor is given by $0 < PF_{DG} < 1$. Induction Generator based in Wind Turbine Generator System comes under Type-2 DG.

c) Type-3 DG: This type of DG injects real power only. Power factor for Type-3 DG is 1. Solar PV System is an example of Type-3 DG.

d) Type-4 DG: It is capable of injecting reactive power only. Power factor is 0 for this type of DG. An example for Type-4 DG is Synchronous Compensator.

V. PROBLEM FORMULATION

The optimum DG allocation can be treated as optimum active power compensation, like capacitor allocation for reactive power compensation. DG allocation studies are relatively new, unlike capacitor allocation. The objective function here is to find the optimal sizes of the DGs (type-2 & Type-3) in terms of standard sizes available in the market and their locations so as to minimize the system loss and improve voltage profile.

A. Power Factor Selection for DG

Type-2 DGs injects real power into the system but consumes reactive power from the system. The power factor of the Type-2 DG is $0 < PF_{DG} < 1$. To find the optimal power factor of DG for a given radial distribution system, fast approach is implemented. According to this approach the power factor of combined total load of the system (PF_D) can be expressed by (1)

$$PF_D = \frac{P_D}{\sqrt{(P_D^2 + Q_D^2)}}$$

Where,
$$P_D = \sum_{i=1}^{N} P_{D_i}$$

$$Q_D = \sum_{i=1}^{N} Q_{D_i}$$

The "possible minimum" total loss can be achieved if the power factor of DG (PF_{DG}) is quickly selected to be equal to that of the total load (PF_D). That can be expressed by (2)

$$PF_{DG} = PF_D$$

For Type-3 DG, power factor is always 1.

B. Solution Methodology

The same Direct Search Algorithm is used again to determine the optimal sizes of DG (Type-2 and

Type-3) together with their optimal locations in radial distribution systems so that maximum possible reduction in losses is achieved. The algorithm is used for radial distribution system with source bus as slack bus and all other load buses as PQ buses. In case of Type-2 DG reactive power consumed from the system is also taken into consideration.

C. Case Studies, Results and Analysis

The Direct Search Algorithm is used for determining the optimal location together with the sizes of Capacitor and DG for loss reduction in the radial distribution system. The algorithm is implemented on 15, 33 and 69 - Bus System. For all the test systems, first individual capacitor and DG (Type-2 and Type-3) placement is done. DG placement along with capacitor is also presented for all the three test systems.

D. Case Study 1: 15 Bus System

This case study is on 15-Bus Radial Distribution System which consists of 15 buses and 14 branches. All the buses are load buses except one slack bus. The total active and reactive power demand of the system is 1266.4 kW and 1251.1 kVAr respectively. 61.80 kW is the base case active power loss of the system.
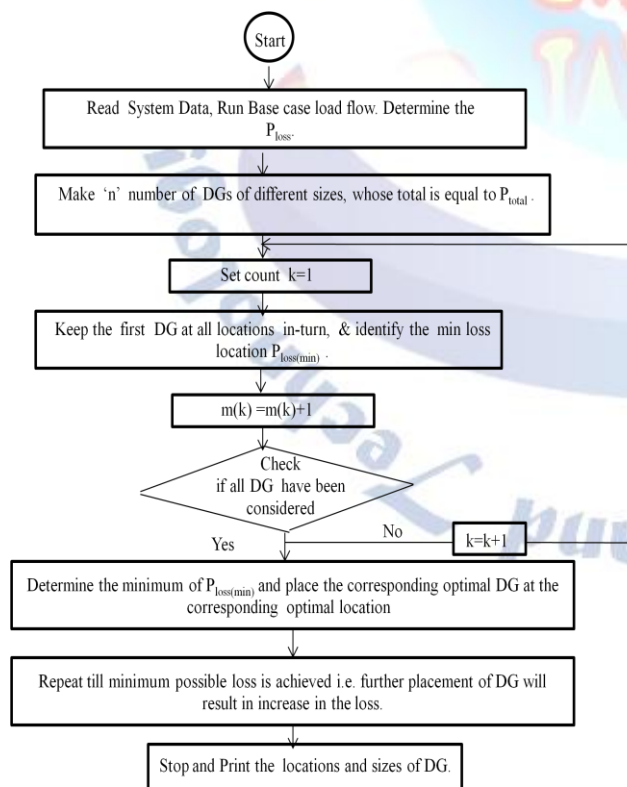

Fig.1 Flowchart for DG Placement using Direct Search Algorithm

Case Study 1 (A): Optimal Placement of Capacitor:

Table 1: Results of Optimal Capacitor Placement in15-Bus System

S.No.	Optimal Capacitor Size (KVAr)	Optimal Location (Bus No.)	Minimum Power Loss after Optimal Capacitor placement (kW)
1	300	4	48.19
2	300	11	39.12
3	300	6	32.48
4	150	15	30.98
5	150	9	**30.30**

Case Study 1 (B): Optimal Placement of Type-3 DG

Table 2: Results of Optimal Placement of Type-3 DG in 15-Bus System

S.No.	Optimal DG Size (kW)	Optimal Location (Bus No.)	Minimum Power Loss after Optimal Placement of DG (kW)
1	500	4	42.86
2	500	6	34.56
3	100	12	32.80
4	100	11	32.13

Case Study 1 (C): Optimal Placement of Capacitor A=and Type-3 DG

Table3: Results of Optimal Capacitor and Type-3 DG Placement in 15- Bus System

S. No.	Optimal DG Size (kW)	Optimal Location (Bus No.)	Minimum Power Loss after Optimal Placement of DG (kW)
1	500	4	12.43
2	500	6	4.57
3	100	12	2.92
4	100	11	**2.29**

Case Study 1 (D): Optimal Placement of Type-2 DG

Table 4: Reactive Power Consumed by various sizes of DGs at 0.7 p.f.

S.No.	Real Power Injected by DG (Type-2) (kW)	Reactive Power Consumed by DG (Type-2) (KVAr)	KVA Rating of DG (Type-2)
1	1000	1020.20	1428.57
2	500	510.048	714.24
3	300	306.024	428.54
4	200	204.02	285.69
5	100	102	142.85

Table 5: Optimal Placement of Type-2 DG on 15- Bus System using Direct Search Algorithm

S.No.	Optimal DG Size (Type-2) (kW)	Optimal Location (Bus No.)	Minimum Power Loss after Optimal Placement of DG (kW)
1	500	2	**68.66**

Case Study 1 (E): Optimal Placement of Capacitor And Type-2 DG

Table 6: Results of Optimal Placement of Capacitor and Type-2 DG in 15- Bus System

S.No.	Optimal DG Size (kW)	Optimal Location (Bus No.)	Minimum Power Loss after optimal placement of DG (kW)
1	500	3	19.70
2	100	6	18.73

Analysis of Results of Case Study On 15-Bus System

Analysis of results of 15-Bus System for the different cases is presented below.

(i) Optimal Placement of Capacitor: The minimum active power loss obtained after making reactive power load demand of the system equal to zero (i.e., at all load buses, Q_{load} =0) is 29.38 kW. This is the minimum possible loss that should be aimed at. Direct Search Algorithm gave 30.30 kW as the minimum loss after optimal placement of capacitor. It can be observed that, the loss obtained after optimal placement of capacitor is very much nearer to the minimum possible loss of the system. There is a reduction of 31.50 kW (50.97%) in the active power loss when compared to the base case value. The optimal sizes of capacitors obtained using the algorithm is 300 and 150 kVAr. Bus number 4, 11, 6, 15 and 9 are the optimal locations for capacitor placement.

(ii) Optimal Placement of Type-3 DG: Table 2 shows the optimum location, corresponding optimum size and total power loss with the corresponding size of the DG (Type-3). The minimum loss obtained after DG placement is 32.13 kW i.e., a reduction of 48.01% in the loss when compared to the base case loss of the system. Any further placement of DG will start to increase the losses and it is likely that it may overshoot the losses of the base case. Also notice that location of DG plays an important role in minimizing the losses.

(iii) Optimal Placement of Capacitor and Type-3 DG: Above two cases presents the minimum possible loss that can be obtained after optimal placement of capacitor and DG (Type-3), individually. In this case capacitors and DGs are placed together to obtained further reduction in the losses. First optimal placement of the capacitors is done (as shown in Table 1) and then DGs are placed optimally to achieve further reduction in the loss (Table 3).2.29 kW is the minimum loss achieved after optimal placement of C & DG (Type-3). The active power loss is reduced by a staggering figure of 96.29%. It can be noticed from Fig. 4.1 that the bus voltage profile has improved significantly (above 0.99 p.u. at all the buses) when compared to base case voltages.

(iv) Optimal Placement of Type-2 DG: The optimal power factor of DG (Type-2) for 15-Bus System is 0.7. From Table 5, it can be noticed that there is no reduction in loss; instead the loss has increased to 68.99 kW from its base case value of 61.80 kW. This is true for any size of DG. The reason is consumption of reactive power by the DG from the system. At 0.7 power factor, DG is consuming more reactive power from the system when compared to the active power injected by the DG. So it can be concluded that Type-2 DG is not suitable for smaller distribution system with lower power factor.

(v) Optimal Placement of Capacitor and Type-2 DG: Here also first capacitors are placed and then optimal placement of DG is done. Table 6 shows the results of optimal placement of DG after the optimal capacitor placement. 18.73 kW is the minimum loss achieved after the optimal placement of C & DG (Type-2). There is a reduction of 69.69% in the active power loss. Better voltage profile is observed when compared to the base case.

E. Case Study 2: 33-Bus System

It is a radial distribution system, with the total load of 3715 kW and 2300 kVAr, having 33 buses and 32 branches. All the buses are load buses except first bus as slack bus. 210.75 kW is the base case active power loss of the system.

Table 7: Reactive Power Consumed by various sizes of DGs at 0.85 p.f.

S.No.	Real Power Injected by DG (Type-2) (kW)	Reactive Power Consumed by DG (Type-2) (KVAr)	KVA Rating of DG (Type-2)
1	1000	619.74	1176.47
2	500	309.87	588.235
3	300	185.92	352.94
4	200	123.95	235.29
5	100	61.97	117.647

Case Study 2 (A): Optimal Placement of Capacitor

Table 8: Results of Optimal Capacitor Placement in 33-Bus System

S. No.	Optimal Capacitor Size (KVAr)	Optimal Location (Bus No.)	Minimum Power Loss after placing the Capacitors in turn (kW)
1	300	32	185.07
2	300	30	167.24
3	300	14	153.29
4	300	30	145.60
5	300	25	142.09
6	300	6	139.81
7	150	24	139.40
8	150	21	139.18
9	150	4	**139.06**

Case Study 2 (B): Optimal Placement of Type-3 DG

Table 9: Results of Optimal Type-3 DG Placement in 33-Bus System

S. No.	Optimal DG Size (kW)	Optimal Location (Bus No.)	Minimum Power Loss after optimal placement of DG (kW)
1	1000	12	129.66
2	1000	30	88.57
3	500	25	77.95
4	300	24	75.28
5	200	21	74.26
6	200	4	73.57
7	100	23	73.36
8	100	7	73.24
9	100	22	73.15
10	100	2	73.13

Case Study 2 (C): Optimal Placement of Capacitor and Type-3 DG

Table 10: Results of Optimal Placement of Capacitor and Type-3 DG in 33-Bus System

S. No.	Optimal DG Size (kW)	Optimal Location (Bus No.)	Minimum Power Loss after optimal placement of DG (kW)
1	1000	12	62.46
2	1000	30	24.24
3	500	25	13.74
4	500	24	10.58
5	100	22	9.92
6	100	21	9.57
7	100	5	9.30
8	100	4	9.17
9	100	20	

Case Study 2 (D): Optimal Placement of Type-2 DG

Table 11: Results of Optimal Placement of Type-2 DG in 33-Bus System

S. No.	Optimal DG Size (kW)	Optimal Location (Bus No.)	Minimum Power Loss after optimal placement of DG (kW)
1	500	12	186.28
2	500	24	179.94
3	300	31	176.32
4	100	21	175.92
5	100	25	175.84

Case Study 2 (E): Optimal Placement of Capacitor And Type-2 DG

Table 12: Results of Optimal Placement of Capacitor and Type-2 DG in 33-Bus System

S.No.	Optimal DG Size (kW)	Optimal Location (Bus No.)	Minimum Power Loss after optimal placement of DG (kW)
1	1000	9	79.18
2	500	32	58.88

3	500	25	49.86
4	200	21	48.93
5	200	24	48.17
6	100	28	48.01
7	100	19	47.99

FIGURE
Analysis of Results Of Case Study on 33-Bus System
Analysis of results of 33-Bus System for the different cases is presented below.

(i) **Optimal Placement of Capacitor:** The minimum active power loss obtained after making reactive power load demand of the system equal to zero (i.e., at all load buses, Q_{load} =0) is 138.4 kW. This is the minimum possible loss that should be aimed at. Direct Search Algorithm gave 139.06 kW as the minimum loss after optimal placement of capacitor. It can be observed that, the loss obtained after optimal placement of capacitor is very much nearer to the minimum possible loss of the system. There is a reduction of 71.69 kW (34.016%) in the active power loss when compared to the base case value. The optimal sizes of capacitors obtained using the algorithm is 300 and 150 kVAr. Bus number 32, 30, 14, 25, 6, 24, 21 and 4 are the optimal locations for capacitor placement.

(ii) **Optimal Placement of Type-3 DG:** Table 8 shows the optimum location, corresponding optimum size and total power loss with the corresponding size of the DG (Type-3). The minimum loss obtained after DG placement is 73.13 kW i.e., a reduction of 65.30% in the loss when compared to the base case loss of the system. Any further placement of DG will start to increase the losses and it is likely that it may overshoot the losses of the base case. Also notice that location of DG plays an important role in minimizing the losses.

(iii) **Optimal Placement of Capacitor and Type-3 DG:** Above two cases presents the minimum possible loss that can be obtained after optimal placement of capacitor and DG (Type-3), individually. In this case capacitors and DGs are placed together to obtained further reduction in the losses. First optimal placement of the capacitors is done (as shown in Table 7) and then DGs are placed optimally to achieve further reduction in the loss (Table 9). 9.08 kW is the minimum loss achieved after optimal placement of C & DG (Type-3). The active power loss is reduced by a staggering figure of 95.69%. It can be noticed from Fig. 4.2 that the bus voltage profile has improved significantly (above 0.99 p.u. at all the buses) when compared to base case voltages.

(iv) **Optimal Placement of Type-2 DG:** The optimal power factor of DG (Type-2) for 33-Bus System is 0.85. The minimum loss obtained after DG placement is 175.82 kW i.e., a reduction of 16.57% in the loss when compared to the base case loss of the system. Any further placement of DG is going to increase the loss. It can be noticed that Type-3 DG placement gives better loss reduction when compared to Type-2 DG.

(v) **Optimal Placement of Capacitor and Type-2 DG:** Here also first capacitors are placed and then optimal placement of DG is done. Table 4.12 shows the results of optimal placement of DG after the optimal capacitor placement. 47.99 kW is the minimum loss achieved after the optimal placement of C & DG (Type-2). There is a reduction of 77.23% in the active power loss. Better voltage profile is observed when compared to the base case.

VI. COST ANALYSIS FOR 15-BUS SYSTEM

Detailed cost analysis for 15-bus system is presented in this section. Average energy cost is calculated as Rs. 5.88 per kWh. Three load levels are considered. They are 160%, 100% and 50% load levels. Three load levels and load duration time data for the system is given in Table 13.

Table 13: Load Level and Load Duration

Load level	0.5 (Light)	1.0 (Normal)	1.6 (Peak)
Duration in a Day (hr)	5	12	7

Cost Analysis with Capacitor Placement Only
Cost analysis with optimal capacitor placement is presented here. The cost of capacitor is taken as Rs. 379 per KVAr (market survey). The total cost of the capacitor is Rs. 4, 54,800.

Table 14: Comparison of results with and without Capacitor Placement

Load Level	Power Loss Before Capacitor Placement (kW)	Power Loss after Capacitor Placement (kW)	Energy Loss Cost before Capacitor Placement (Rs.)	Energy Loss Cost after Capacitor Placement (Rs.)
Light (0.5)	14.70	7.38	1,57,745.7	79,194.78
Nominal (1.0)	61.80	30.30	15,91,621.92	7,80,358.32
Peak (1.6)	168.91	93.71	25,37,602.494	14,07,842.814
Total Cost			42,86,970.114	22,67,395.914
Annual Net Saving = Rs. 24,74,374.2				

Table 14 shows the power loss and annual energy loss cost for each loading condition. The annual net saving is obtained by subtracting total cost of capacitor and annual total energy loss cost after capacitor placement from annual total energy loss cost before capacitor placement.

Cost Analysis for C & DG (Type-2) Placement

Induction generator based Wind Energy System (Type-2 DG) is optimally placed together with switched capacitor. The total size of the DG and capacitor is 600 kW 1200 kVAr respectively. A comparison of results, with and without C & DG (Type-2) placement, is presented in table 15 for various loading condition.

Table 15: Comparison of results with and without C & DG (Type-2) Placement

Load Level	Power Loss after C & DG (Type-2) Placement (kW)	Power Loss after C & DG (Type-2) Placement (kW)	Energy Loss Cost before C & DG (Type-2) Placement (Rs.)	Energy Loss Cost after C & DG (Type-2) Placement (Rs.)
Light (0.5)	14.70	4.14	1,57,745.7	44,426.34
Nominal (1.0)	61.80	18.73	15,91,621.92	4,82,379.912
Peak (1.6)	168.91	81.71	25,37,602.494	12,27,562.014
Total Energy Loss Cost (Annual)			42,86,970.114	17,54,368.266

Calculation of Capital Return

Calculation of capital return is done as below:
- Energy Cost = Rs. 5.88/kWh
- Cost of Capacitor = Rs. 379/KVAr

- Total capital Cost of Wind Energy System (Type-2 DG) = Rs. 5.5 Cr/ MW
- Energy Cost of Wind Energy System = Rs. 4/kWh
- Total Cost of DG installation (C_{DG}) = $0.6*5.5*10^7$ = Rs.3,30,00,000
- Total Cost of Capacitor installation (C_{Cap}) = Rs. 4,54,800

Before C & DG placement, active power supplied from slack bus is 1288.2 kW and after C & DG placement is 1245.15 kW. Difference between these two quantities is 43.05 kW. The profit of this power release is calculated as follow:

- Profit from the release of power (Annually)
  = 43.05*5.88*365*24
  = Rs. 22,17,453.84

Now the total cost is calculated as follows:
- Total Cost after C& DG placement = C_{DG} + C_{Cap} + Annual Energy Loss Cost after C & DG (Type-2) placement - Profit from the release of power
  = Rs. 3,29,91,714.426
- Capital Return Period (Years) =

$$\frac{\text{Total Cost after C\& DG placement}}{\text{Annual Energy Loss Cost before C \& DG placement}}$$

  = 3, 29, 91,714.426 **/** 42, 86,970.114
  = 7.69 Years

So the capital cost can be recovered in approximately 8 years. After this period the utility will get a net saving of Rs. 25,32,601.85 annually.

Cost Analysis for C & Dg (Type-3) Placement

Solar photo voltaic system (Type-3 DG) is optimally placed together with switched capacitor. The total size of the DG and capacitor is 1200 kW 1200 kVAr respectively. A comparison of results, with and without C & DG (Type-3) placement, is presented in table 16 for various loading condition.

Table 16: Comparison of results with and without C & DG (Type-3) Placement

Load Level	Power Loss after C & DG (Type-3) Placement (kW)	Power Loss after C & DG (Type-3) Placement (kW)	Energy Loss Cost before C & DG (Type-3) Placement (Rs.)	Energy Loss Cost after C & DG (Type-3) Placement (Rs.)
Light (0.5)	14.70	1.75	1,57,745.7	18,779.25
Nominal (1.0)	61.80	2.29	15,91,621.92	58,977.576
Peak (1.6)	168.91	25.81	25,37,602.494	71,483.8922
Total Energy Loss Cost (Annual)			**42,86,970.114**	**1,49,240.7182**

Calculation of Capital Return

Calculation of capital return is done as below:

- Energy Cost = Rs. 5.88/kWh
- Cost of Capacitor = Rs. 379/KVAr
- Total capital Cost of Solar Photo Voltaic System = Rs. 7.97 Cr/ MW
- Energy Cost of Solar Power = Rs. 6.49/kWh
- Total Cost of DG installation (C_{DG}) = 1.2 *7.97*10^7 = Rs. 9,56,40,000
- Total Cost of Capacitor installation (C_{Cap}) = Rs. 4,54,800

Before C & DG placement, active power supplied from slack bus is 1288.2 kW and after C & DG placement is 1228.69 kW. Difference between these two quantities is 59.51 kW.

The profit of this power release is calculated as follow:

- Profit from the release of power (Annually) = 59.51*5.88*365*24 = Rs. 30,65,288.68

Now the total cost is calculated as follows:

- Total Cost after C& DG placement = C_{DG} + C_{Cap} + Annual Energy Loss Cost after C & DG (Type-2) placement - Profit from the release of power = Rs. 9,31,78,752.0382

- Capital Return Period (Years) =

$$\frac{\text{Total Cost after C\& DG placement}}{\text{Annual Energy Loss Cost before C \& DG placement}}$$

= 9,31,78,752.0382 / 42,86,970.114
= 21.75 Years

So the capital cost can be recovered in approximately 22 years.

Cost Analysis for 33-Bus System

Cost Analysis with Capacitor Placement Only

2250 kVAr is the total size of capacitor used for loss reduction in the 33-bus system. The total cost of the capacitor came out to be Rs. 8,52,750. Table 5.5 shows the comparison between power loss and annual energy loss cost before and after placement of capacitor for all the given loading condition. An annual net saving of Rs. 41,81,119.176 is obtained.

Table 17: Comparison of results with and without Capacitor Placement

Load Level	Power Loss Before Capacitor Placement (kW)	Power Loss after Capacitor Placement (kW)	Energy Loss Cost before Capacitor Placement (Rs.)	Energy Loss Cost after Capacitor Placement (Rs.)
Light (0.5)	48.76	32.77	5,23,243.56	3,51,654.87
Nominal (1.0)	210.75	139.06	54,27,739.8	35,81,406.864
Peak (1.6)	602.12	401.37	90,45,889.608	60,29,942.058
Total			1,49,96,872.968	99,63,003.

Cost				792
Annual Net Saving = Rs. 41,81,119.176				

Cost Analysis for C & DG (Type-2) Placement

Induction generator based Wind Energy System (Type-2 DG) is optimally placed together with switched capacitor. The total size of the DG and capacitor is 2600 kW 2250 kVAr respectively. A comparison of results, with and without C & DG (Type-2) placement, is presented in table 18 for various loading condition.

Table 18: Comparison of results with and without C & DG (Type-2) Placement

Load Level	Power Loss after C & DG (Type-2) Placement (kW)	Power Loss after C & DG (Type-2) Placement (kW)	Energy Loss Cost before C & DG (Type-2) Placement (Rs.)	Energy Loss Cost after C & DG (Type-2) Placement (Rs.)
Light (0.5)	14.70	4.14	1,57,745.7	44,426.34
Nominal (1.0)	61.80	18.73	15,91,621.92	4,82,379.912
Peak (1.6)	168.91	81.71	25,37,602.494	12,27,562.014
Total Energy Loss Cost (Annual)			42,86,970.114	17,54,368.266

Calculation of Capital Return

Calculation of capital return is done as below:

- Energy Cost = Rs. 5.88/kWh
- Cost of Capacitor = Rs. 379/KVAr
- Total capital Cost of Wind Energy System (Type-2 DG) = Rs. 5.5 Cr/ MW
- Energy Cost of Wind Energy System = Rs. 4/kWh
- Total Cost of DG installation (C_{DG}) = 2.6*5.5*10^7 = Rs.14,30,00,000
- Total Cost of Capacitor installation (C_{Cap}) = Rs. 8,52,750

Before C & DG placement, active power supplied from slack bus is 3925.75 kW and after C & DG placement is 3762.99 kW. Difference between these two quantities is 162.76 kW.

The profit of this power release is calculated as follow:

- Profit from the release of power (Annually) = 162.76*5.88*365*24 = Rs. 83,83,572.288

Now the total cost is calculated as follows:

- Total Cost after C& DG placement = C_{DG} + C_{Cap} + Annual Energy Loss Cost after C & DG (Type-2) placement - Profit from the release of power = Rs. 14,06,19,735.78

- Capital Return Period (Years) =

$$\frac{\text{Total Cost after C\& DG placement}}{\text{Annual Energy Loss Cost before C \& DG placement}}$$

= 14,06,19,735.782 **/** 1,49,96,872.968

= 9.37 Years

So the capital cost can be recovered in approximately 9.5 years. After this period the utility will get a net saving of Rs. 98,46,314.898 annually.

Cost Analysis for C & DG (Type-3) Placement

Solar photo voltaic system (Type-3 DG) is optimally placed together with switched capacitor. The total size of the DG and capacitor is 3500 kW 2250 kVAr respectively. A comparison of results, with and without C & DG (Type-3) placement, is presented in table 19 for various loading condition.

Calculation of Capital Return

Calculation of capital return is done as below:

- Energy Cost = Rs. 5.88/kWh
- Cost of Capacitor = Rs. 379/KVAr
- Total capital Cost of Solar Photo Voltaic System = Rs. 7.97 Cr**/** MW
- Energy Cost of Solar Power
  = Rs. 6.49/kWh
- Total Cost of DG installation (C_{DG})
  = 3.5*7.97*10^7 = Rs. 27,89,50,000
- Total Cost of Capacitor installation (C_{Cap})
  = Rs. 8,52,750

Table 19: Comparison of results with and without C & DG (Type-3) Placement

Load Level	Power Loss after C & DG (Type-3) Placement (kW)	Power Loss after C & DG (Type-3) Placement (kW)	Energy Loss Cost before C & DG (Type-3) Placement (Rs.)	Energy Loss Cost after C & DG (Type-3) Placement (Rs.)
Light (0.5)	48.76	2.34	5,23,243.56	25,110.54
Nominal (1.0)	210.75	9.08	54,27,739.8	2,33,849.952
Peak (1.6)	602.12	76.76	90,45,889.608	11,53,196.184
Total Energy Loss Cost (Annual)			1,49,96,872.968	14,12,156.676

Before C & DG placement, active power supplied from slack bus is 3925.75 kW and after C & DG placement is 3724.08 kW. Difference between these two quantities is 201.67 kW.

The profit of this power release is calculated as follow:

- Profit from the release of power (Annually)
  = 201.67*5.88*365*24
  = Rs. 1,03,87,779.7

Now the total cost is calculated as follows:

- Total Cost after C& DG placement = C_{DG} + C_{Cap} + Annual Energy Loss Cost after C & DG (Type-2) placement - Profit from the release of power
  = Rs. 27,08,27,126.976

- Capital Return Period (Years) =

$$\frac{\text{Total Cost after C\& DG placement}}{\text{Annual Energy Loss Cost before C \& DG placement}}$$

= 27,08,27,126.976 **/** 1,49,96,872.968

= 18.05 Years

So the capital cost can be recovered in approximately 18 years.

Cost Analysis Limitations

Following are the limitation of cost analysis presented in this dissertation work:

1. Cost function is not included in the objective function while determining the optimal size of capacitor and DG. The main objective is to minimize the loss without considering the cost.
2. Cost analysis is done only on the basis of loss reduction. Other monetary benefits obtained by installation of DGs are not included.
3. Urban feeder with only domestic, industrial and commercial load is considered in this work. Hence the energy cost is calculated by taking average of per unit cost of above three loads.

VII. CONCLUSION

In this work, Direct Search Algorithm is implemented to determine the optimal sizes of Capacitors and DGs along with their optimal locations for loss reduction in the Radial Distribution Systems. Switched Capacitor, Type-2 and Type-3 DGs are considered for loss reduction. Case studies are carried out on three standard test systems: 15-bus system, 33-Bus System and 69-Bus System. It is observed that there is a highest reduction in the real power loss along with improvement in the voltage profile of the distribution systems when both Capacitors and DGs are used. Type-3 DG gives much reduction in loss compared to Type-2 DG, individually or along with Capacitor placement. With respect to base case power loss, there is a reduction of 96.29%, 95.69% and 96.76% in the power loss for 15-Bus System,   33-Bus System and 69-Bus System

respectively after placing Capacitors and Type-3 DGs and a reduction of 69.69%, 77.23% and 82.50% respectively with Capacitors and Type-2 DGs. Cost analysis of Capacitor and DG Placement is done for all the three standard test systems. Net saving is obtained when only capacitors are used for loss reduction. Because of high initial cost of installation, capital return period for Type-3 DG is more when compared to Type-2 DG. Hence it is concluded that loss reduction is achieved either through Capacitor or DG placement but highest reduction is obtained by combination of both.

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