Evaluation of additional Power loss reduction in DG integrated optimal Distribution Network

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Abstract: Distribution network (DN) is a very complex network facing several technical problems such as power loss, drop in bus voltage etc. During the past few decades, optimal allocation and sizing of capacitors have played a significant role in addressing the above issues. Power loss minimization considering single and two Distributed Generation (DG) units with and without Network Reconfiguration (NR) via Autonomous Group Particle Swarm Optimization (AGPSO) under five different cases has already been discussed. This paper proposes an application of AGPSO to solve the Optimal Capacitor Allocation Problem (OCAP) with an objective to achieve additional real power loss reduction after optimal allocation and sizing of single and two DGs with NR subject to satisfying equality and inequality constraints. Further, a comprehensive study has been conducted to ascertain the impact of capacitors on additional power loss minimization starting from single optimal node upto four nodes in the reconfigured DG integrated DN. This developed technique is demonstrated using the same two test systems (IEEE 33 and 69) that have been considered previously. The results obtained using AGPSO, reveal that the developed technique effectively achieves additional power loss suppression and enhancement in bus voltage.

Keywords: Optimal CAP, Optimal Distribution Network, Additional Power Loss Reduction, Bus Voltage Profile, AGPSO.

1. INTRODUCTION

The main purpose of the DN is to meet the customer demands reliably and economically in an efficient manner. In general, the structure of DN has radial configuration. But its operation becomes complex. It has been normally agreed that most of the power losses occur in the DNs compared to transmission network, due to its high R/X ratio. Moreover due to the steep growth in power demand, the power loss (I^2R) increase results in reduction in bus voltage and efficiency. Also as the distance between the buses and substation increases, the bus voltage decreases. However, in India considering Transmission and Distribution, the average power loss has been estimated between 26% and 27% of the power generated (S.G. Ankaliki and Katti, 2012). It is well-known that major power loss occurs at distribution part which is on the higher side compared to acceptable norms. Therefore, finding some suitable and efficient method for this problem becomes crucial.

Capacitors at optimal locations with appropriate sizes have maximized the voltage regulation, power loss reduction, increased feeder capacity release, reduction in KVA demand, improvement in power factor at the sub-station bus etc. Since capacitors lower the reactive requirement from the main source, higher real power output is available (William D. Stevenson, 2004).

OCAP has analyzed by the researchers since 1960s. Hitherto many articles have focused on the capacitor placement problem using classical methods (Hogan et al., 2005; Khodr et al., 2008) numerical and mathematical based methods (Ng et al., 2000; Jabr, 2008) and heuristic (Venkatesh et al., 2004; Hamouda and Sayah, 2013). From

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(Gampa and Das, 2016; Sultana and Roy, 2014, 2016), it has been understood that classical gradient based and conventional techniques had not been successful in getting optimum solutions.

Since the problem is of large dimensional, mixed integer, complex combinatorial and nonlinear in nature, the most widely used way to solve the problem is to use meta-heuristic optimization method which can handle discrete non-linear optimization problem efficiently (Sultana and Roy, 2016). In recent times, numerous approaches related to meta-heuristics optimization algorithms have been applied to solve the OCAP considering cost based objective function (Sultana and Roy, 2016; Nawaz et al., 2017; Das and Banerjee, 2013; Reddy and Reddy, 2017; Oscar D. Montoya Giraldo and Arevalo, 2017; Devi and Lakshminarasimman, 2017), (Sukraj et al., 2018; Abdelaziz et al., 2016; Devabalaji et al., 2018; Ali et al., 2016; Bagheri et al., 2017; Prakash and Lakshminarayana, 2017). Out of them, nature inspired based soft computing techniques are more popular. Some of the papers have dealt with the capacitor placement problem considering the capacitor treated as a continuous variable instead of discrete types (Sultana and Roy, 2016; Nawaz et al., 2017; Das and Banerjee, 2013; Reddy and Reddy, 2017; Oscar D. Montoya Giraldo and Arevalo, 2017; Devi and Lakshminarasimman, 2017), (Devabalaji et al., 2018). On the other hand, available commercial capacitors are of discrete types and continuous variable methodology might not yield optimal result (Baghzouz and Ertem, 1990). Sensitivity Index based optimal node selection for capacitor placement has been followed by many authors (Das and Banerjee, 2013), (Sukraj et al., 2018; Abdelaziz et al., 2016; Devabalaji et al., 2018; Ali et al., 2016; Bagheri et al., 2017; Prakash and Lakshminarayana, 2017). Though sensitivity based index helps in reduction of search space during optimization, from (Haldar and Chakraborty, 2015), it is understood that power loss sensitivity index (PLSI) based approach for selection of high potential buses for capacitor placement may not always indicate the appropriate node or guarantee the best locations. One drawback of this method is the calculations burden as the Load Flow (LF) requires running for times equal number of buses before starting the optimisation (El-Fergany and Abdelaziz, 2014).

Though meta-heuristic optimization techniques are effective in determining optimal nodes for capacitor allocation problem, many of the optimization techniques have drawbacks as they may not guarantee reaching optimal value and are difficult to escape from the local minima (Prakash and Lakshminarayana, 2017). Therefore, there is a need to present a simple, effective, fast and efficient population based optimization technique to solve complex DN problems which are essential. Allocation and sizing of DGs and capacitors at three and four optimal nodes considering Network reconfiguration has been done by (Srinivasan and Visalakshi, 2017). The difference between (Srinivasan and Visalakshi, 2017) and (Srinivasan and Visalakshi, 2016) is the number of DG locations for optimization. (Srinivasan and Visalakshi, 2016) dealt optimization using single and two DG units with NR. Conversely, (Srinivasan and Visalakshi, 2017) discussed the problem using three and four DG units with NR.

In view of the above, this article is an extension of (Srinivasan and Visalakshi, 2016) where AGPSO has been utilized to solve the objective function. The outcome of the (Srinivasan and Visalakshi, 2016) has been taken as the first stage of power loss minimization. To achieve maximum additional power loss reduction in the reconfigured single / two DG incorporated DN, this work considers, the same optimization technique (AGPSO) to solve the optimal placement and capacity determination of capacitors starting from single to four nodes; it has been projected as the subsequent stage of power loss minimization. The node voltage profile has been improved further and significant additional power loss reduction is also achieved compared to (Srinivasan and Visalakshi, 2016). The method has been tested and demonstrated using the same two test systems (IEEE 33 and 69 bus) considered in (Srinivasan and Visalakshi, 2016).

The total article has been arranged in five sections. Section 2 deals with the objective function and data structure based power flow which is embedded in the optimization algorithm. Section 3 discusses the concept of proposed methodology (AGPSO) and its application to solve the optimal placement and sizing of capacitors in reconfigured DG integrated radial DN. Debates on the simulation and the results have been done in Section 4. Finally Section 5 concludes the results followed by references and APPENDIX.

2. PROBLEM FORMULATION

The ultimate aim of this work is to solve the OCAP, in reconfigured DG integrated DN which is also an operational planning problem, to achieve additional power loss reduction subject to satisfying equality and inequality constraints.

2.1 Objective Function

$$fit = \left[\frac{\mathrm{TP}_{\mathrm{Loss(ACI)}}}{\mathrm{TP}_{\mathrm{Loss(BCI)}}}\right]. \tag{1}$$

Subject to equality constraints

$$Q_{MS} - \sum Q_D + \sum_{t=1}^{NC} Q_{c(t)} - TQ_{LOSS} = 0. \tag{2}$$

Subject to inequality constraints

$$Q_{c(t)}^{min} \leq Qc(t) \leq Q_{c(t)}^{min}, \tag{3}$$

$$\sum_{t=1}^{NC} Q_{c(t)} \leq \sum Q_D, \tag{4}$$

$$V_{(t)}^{min} \leq V_{(t)} \leq V_{(t)}^{max}. \tag{5}$$

where

$$TP_{Loss} = \sum_{t=1}^{TB} P_{Loss(t)}$$

2.2 DN Load Flow with DG

LF used in the DNs contains no DG units. However 'Green' power DG units such as wind, PV and small hydro generation can be integrated into the DNs by modifying the traditional LF suitable for integration of Renewable Energy type DGs.

It is well known that the purpose of LF is to analyze the performance of the network for both planning and operation stages. Existing matrix-based LF methods such as Newton-Raphson (NR) and Fast Decoupled LF (FDLF) (Tinney and Hart, 1967; Stott and Alsac, 1974) were inferior in solving the power balance equations effectively and efficiently because of the above problems which deteriorated the diagonal dominance of the Jacobian matrix and radial nature of the network. Even after some modifications in the NRLF, the computation time for convergence is large enough. Subsequently, LF based on ladder theory (Kersting, 1984) was developed. Yet it has been reported that it does not obtain solutions for several instances since it involves matrices and also from (Stevens et al., 1986), it is evidenced that though these DNLF methods seem to be the fastest, they could not converge in five out of twelve cases studied. Later Backward/Forward Sweep Method (BFSM) based LF analysis has been developed for radial DN (Augugliaro et al., 2010). Though BFSM is used by many researchers, it is understood that, BFSM suffers from drawbacks which needs some modifications to use in modern DN. A fast, flexible, robust and efficient method is necessary to solve the power balance equation for radial DN efficiently. The Recursive function and a linked-list data structure designed LF is used in this work to solve OCAP in the reconfigured DG integrated radial DN (Rost et al., 2006).

3. INTRODUCTION TO AGPSO AN ITS CAPABILITY TO SOLVE OCAP

Particle swarm optimization (PSO) is one of the population based evolutionary algorithms based on the behaviour of swarms which was introduced by (Eberhart and Kennedy, 1995) in 1995. Much importance has been given to PSO due to its simplicity; ease of implementation and less memory requirement for solving several engineering optimization problems during the past two decades.

3.1 Autonomous Group Particle Swarm Optimization

Updating strategies of autonomous groups can be implemented with any continuous function whose range is in the interval [0, L]. Four groups have been defined based on termite colonies which have their own patterns to search the problem such as search space locally and globally. Three different versions of Particle Swarm Optimization (PSO) with different autonomous groups named AGPSO1, AGPSO2, and AGPSO3 have been developed with diverse range of functions. They are used to investigate their effects on the performance of PSO to form as AGPSO. To investigate the efficiency of these characteristics in improving the performance of PSO, this modified algorithm proposes a mathematical model of different functions with diverse slopes, curvatures, and interception points. These are employed to tune socio and cognitive constants of C_1 and C_2. Three groups of PSO have different types of functions with different patterns and changes during the course of the iterations. The dynamic coefficients with different functions of AGPSO were given in (Mirjalili et al., 2014). Table 1 indicates the minimum and maximum value of capacitors (kVAr) from single node upto four optimal nodes for scenario 1 and 2. Detailed description about AGPSO has been available in (Mirjalili et al., 2014) with the merits of AGPSO compared with variants of PSO.

Table 1. Typical Value of Agents (Cases VI to VIII)

Variable	Solution Vectors (SV)	Variables	Range
$X^{(15)}$ $X^{(17)}$ $X^{(19)}$ $X^{(21)}$	Node No. 3 to 33 / 3 to 69	$X^{(16)}$ $X^{(18)}$ $X^{(20)}$ $X^{(22)}$	0.15 - 2.1 MVAr (in discrete steps of 0.15 MVAr)

3.2 Application of AGPSO for the chosen problem

The application of AGPSO in optimal allocation and sizing of capacitors in the DG allocated reconfigured DN to achieve additional real power loss minimization which has been described in this segment. The steps for the AGPSO for optimal capacitor placements are given below:

Step 1: Initialize the particles X_i of PSO randomly within the boundary limits according to Table 1. Since this work considers optimal allocation of capacitors upto four nodes, the number of particles are equal to eight. Optimal Node for capacitor allocation and its corresponding sizing are represented as N_{cap} and K_{cap}. Thus the total number of particles are twenty two which is inclusive of variable values obtained in (Srinivasan and Visalakshi, 2016) as given in equation (6), where, 'T' indicates the population size from a set of random distributions. The values obtained under cases III to V are already discussed in (Srinivasan and Visalakshi, 2016) which all occupy the first fourteen positions. Two of each capacitor node and sizing occupy the remaining eight. Only the particles that satisfy all the constraints will be considered as the initial population. Table 1 indicates the minimum and maximum values of capacitors for four optimal nodes.

$$X_{(iT)} = \begin{bmatrix} \text{Tie} - \text{switch status (1to5)} \\ \text{Status of opening of sectionalizing switches (6to10)} \\ \text{DG bus limits } (11,13) \\ \text{DG sizing limits } (12,14) \\ N_{Cap,1}, K_{Cap,1}, N_{Cap,2}, K_{Cap,2} \\ N_{Cap,3}, K_{Cap,3}, N_{Cap,4}, K_{Cap,4} \end{bmatrix}^{T}_{22X1} \tag{6}$$

Step 2: Particles X_i are randomly split into some predefined autonomous groups with beneficiary functions according to Table 1 (Mirjalili et al., 2014).

Step 3: gbest, pbest, and the fitness given in equation (1) of each particle (X_{iT}) at each iteration has been calculated.

Step 4: For each particle, the coefficients C_1 and C_2 have been updated using its group's strategy.

Step 5: Velocities and positions of particles have been updated using equation (7)-(8).

$$V_i^{t+1} = (w \cdot V_i^t) + (C_1 \cdot rand \cdot (P_{best_i} - X_i^t)) + (C_2 \cdot rand \cdot (g_{best_i} - X_i^t)) \tag{7}$$

$$X_i^{t+1} = X_i^t + V_i^{t+1} \tag{8}$$

Change in variable parameters can be obtained by substituting equation (6) into (7) and (8) when the particles change from the existing position to a new position, former inferior vectors will get replaced by newly generated vectors obtained at the end of each iteration. This process cycle gets completed once maximum number of iteration is reached. For both the test systems, the parameters detail

Table 2. Performance of AGPSO in OCAP – 33 Bus system (Scenario 1)

Parameters	Case VI	Case VII	Case VIII
CAPACITORS AT SINGLE OPTIMAL NODE			
Capacitor size (KVAr) / (Bus No.)	1200 (30)	1200 (30)	1050 (30)
PLoss (KW)	48.488	45.925	32.13
QLoss (KVAr)	43.442	50.971	35.006
% Additional PLoss reduction	17.6475	13.894	15.9725
Total PLoss reduction	77.02%	78.23%	84.77%
Vmin (p.u) / Bus No.	0.96771 (14)	0.96715 (18)	0.97127 (14)
CAPACITORS AT TWO OPTIMAL NODES			
Capacitor size (KVAr) / (Bus No.)	900 (30) 750 (7)	1050 (30) 600 (8)	1050 (30) 600 (8)
PLoss (KW)	43.908	40.411	28.918
QLoss (KVAr)	40.632	45.813	32.505
% Additional PLoss reduction	19.8185	16.50724	17.495
Total PLoss reduction	79.19%	80.85%	86.30%
Vmin (p.u) / Bus No.	0.97387(14)	0.9736 (14)	0.98092 (16)
CAPACITORS AT THREE OPTIMAL NODES			
Capacitor size (KVAr) / (Bus No.)	900 (30) 450 (8) 450 (24)	1050 (30) 600 (8) 300 (6)	1050 (30) 600 (8) 300 (6)
PLoss (KW)	41.183	39.151	27.772
QLoss (KVAr)	38.258	45.113	31.865
% Additional PLoss reduction	21.1095	17.10424	18.038
Total PLoss reduction	80.48%	81.45%	86.84%
Vmin (p.u) / Bus No.	0.97692(14)	0.97683(14)	0.9829 (16)
CAPACITORS AT FOUR OPTIMAL NODES			
Capacitor size (KVAr) / (Bus No.)	900 (30) 450 (8) 450 (24) 300 (12)	1050 (30) 450 (8) 300 (6) 150 (18)	900 (30) 450 (8) 300 (6) 300 (24)
PLoss (KW)	39.341	38.796	26.984
QLoss (KVAr)	36.064	44.585	30.275
% Additional PLoss reduction	21.9825	17.273	18.4114
Total PLoss reduction	81.36%	81.61%	87.21%
Vmin (p.u)/ Bus No.	0.97744 (14)	0.97808 (14)	0.98371(13)

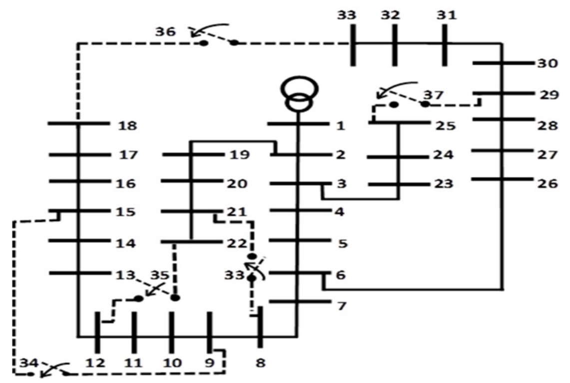

Fig. 1. IEEE 33 bus test system : Base Case

such as agent size and the number of iterations which are selected as 800 and 100 respectively.

4. CASE STUDY DETAILS AND RESULTS

First test system has 33 buses, 37 switches and five looping branches as shown in Fig. 1 and another system has 69 buses, 7 lateral feeders and 73 switches as shown in Fig. 2. Both systems have 5 tie-switches and the system voltage is 12.66 KV. The base MVA and base KV for both the test cases are taken as 100 and 12.66 respectively. Node No.1 (main Sub-station node) is considered as slack node and all other nodes are considered as load nodes. AGPSO coding has been developed in MATLAB software and run on an Intel i5 third generation processor with 3 GB RAM. The minimum and maximum voltages have been set as 0.95 p.u. and 1.05 p.u. From the three outputs (AGPSO1, AGPSO2 and AGPSO 3), only the least output that corresponds to each iteration has been considered as the best value which are tabulated in the corresponding Table from 2 to 5.

This work considers, optimal placement and sizing of capacitors which starts from single node upto four nodes in the reconfigured DG integrated radial DN under three different cases (Cases from VI to VIII) after (Srinivasan and Visalakshi, 2016) to identify the effectiveness of the AGPSO in achieving additional power loss minimization.

Cases I to V: Discussed in (Srinivasan and Visalakshi, 2016)

Case VI: Additional power loss reduction, has been assessed using allocation and sizing of capacitors from single optimal node to four nodes after case III (Srinivasan and Visalakshi, 2016).

Case VII: The effect of additional power loss minimization has been investigated by allocation of capacitors optimally from single node to four nodes after case IV (Srinivasan and Visalakshi, 2016)

Case VIII: Further power loss reduction using capacitors have been estimated at the optimal nodes from single one to four nodes after case V (Srinivasan and Visalakshi, 2016).

4.1 IEEE 33 Bus Test system - Results & Discussions

The total apparent power supplied by the main source is (3.715+j 2.3) MVA. The line data and load data for this network were taken from (Venkatesh et al., 2004). For IEEE 33 bus test system, the total system real and reactive power losses with poor bus voltage had been recorded in (Venkatesh et al., 2004). The results obtained have been summarized in Table 2 and 3 for all the cases and scenarios.

Considering Scenario 1 and from Table 2, it is clear that case VI achieves additional power loss reduction from 17.6475% to 21.9825% after optimal placement of capacitors from single node to four nodes. The total power loss reduction under case VI seems to be between 77% and 81.355%. Bus voltage improvements appeared between 0.00546 and 0.01519 p.u compared to case III. Considering case VII, after optimal allocation of capacitors from single node to four nodes, the additional power loss reduction achieved is between 13.894% and 17.273%. The total power loss reductions are found to be 78.2346%, 80.848%, 81.445% and 81.6133% respectively as indicated in Table 2. The bus voltage improvements before and after

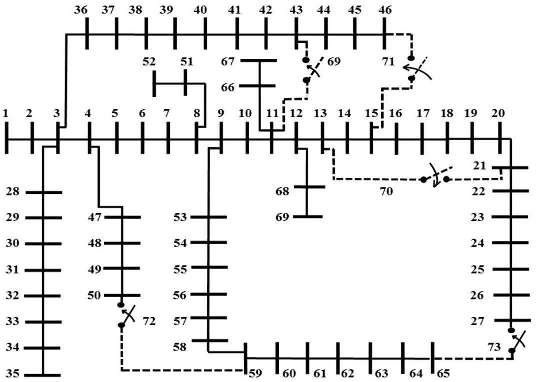

Fig. 2. IEEE 69 Bus test system – Base Case

capacitor placements are between 0.00643 and 0.01736 p.u. compared to case IV.

Considering case VIII, additional power loss reductions from 15.9725% to 18.4114% are achieved after optimal allocation of capacitors up to four nodes. After case VIII, total power loss reductions are found to be 84.7725%, 86.295%, 86.838% and 87.2113%. Bus voltage improvement before and after optimal capacitor placement seemed to be between 0.00334 and 0.1578 p.u.

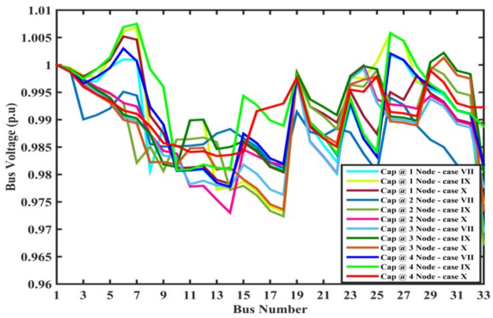

Fig. 3. Bus Voltage profile post capacitor placement – 33 Bus test system – Scenario 1

Considering Scenario 2 and from Table 3, additional power loss reductions under case VI are between 16.48385% and 19.767% after optimal capacitor allocation from single node to four nodes and thus the total power loss reductions achieved are 83.1284%, 84.8962%, 86.2% and 86.412% respectively. The bus voltage improvements after case VI increased from 0.01385 to 0.02324 p.u. Power loss reductions after case VII are found to be between 14.078% and 17.17%. Thus the total power loss reductions achieved are 88.0635%, 90.435%, 90.965% and 91.155% respectively. Node voltage improvements after case VII are found to be between 0.01278 and 0.02318 p.u. After case VIII, the additional power loss reductions witnessed are between 12.7505% and 16.512% after optimal capacitor placement from single to four nodes. The total power loss reductions gained are 91.464%, 94.723%, 95.051% and 95.225% respectively. The bus voltages have been enhanced between 0.00812 p.u and 0.0203 p.u.

From the above discussion, it is evident that maximum power loss reductions after optimal capacitor allocation at four nodes yield more power loss reduction than single node to three nodes. However the power loss reduction differences beyond two nodes are below 1% only with the bus voltages improved in all cases. Though additional power loss reduction improvement under case VI are high compared to other cases, maximum total power loss reduction under case VIII appear to be the highest. From the above results achieved, it is evident that case VIII minimizes the power loss in a proficient manner compared to allocation and sizing of four DG units, simultaneously with NR (Dahalan et al., 2014; Mohd Dahalan et al., 2015) from economic and investment point of view. Fig. 3 and 4 show the node voltage obtained after optimal allocation of capacitors considering all the cases and scenario 1 & 2.

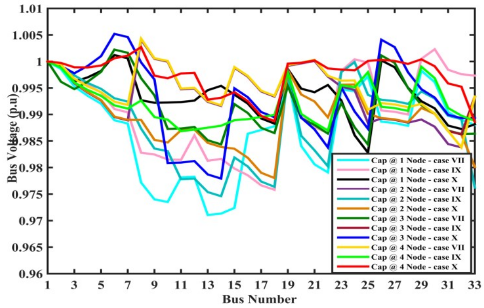

Fig. 4. Bus Voltage profile post capacitor placement – 33 Bus test system – Scenario 2

4.2 IEEE 69 Bus Test system - Results & Discussions

The total connected loads on this hypothetical system are 3802.19 kW and 2694.60 KVAr respectively with system voltage as 12.66 KV. The data for this network has been taken from (Savier and Das, 2007). Similar to IEEE 33 bus test system, base case values for this test system were recorded in (Savier and Das, 2007). The results obtained using the proposed method are tabulated in Table 4 and 5 for all cases and scenarios.

Table 4, points out that after case VI, power losses further reduced from 8.377% to 11.7126% compared to (Srinivasan and Visalakshi, 2016) and total power loss reductions seemed to be 87.261%, 89.6146%, 90.341% and 90.5966% respectively. The bus voltages improvements after case VI are found to be between 0.00207 and 0.00953 p.u. The additional power loss reduction achieved under case VII is between 8.054% and 11.759% and the total power loss reductions are 87.327%, 89.968%, 90.7375% and 91.033% respectively. The bus voltages have been upgraded between 0.00385 and 0.01372 p.u. Considering case VIII, additional power loss minimizations achieved is between 11.7065% and 13.5773%. However the total power loss reductions have reached to 93.404%, 94.218%, 94.945% and 95.271% respectively. The bus voltage improvements have been enhanced between 0.00512 and 0.01133 p.u.

From Table 5, it is obvious that optimal allocation of capacitors at single node to four nodes under case VI yield an additional power loss reduction from 9.3728% to 12.8903%. Accordingly the total real power loss reductions have increased to 92.1925%, 94.6913%, 95.4674% and 95.71% respectively. The bus voltages have improved between 0.00692 and 0.01347 p.u. The additional power

Table 3. Performance of AGPSO in OCAP – 33 Bus system (Scenario 2)

Parameters	Case VI	Case VII	Case VIII
	CAPACITORS AT SINGLE OPTIMAL NODE		
Capacitor size (KVAr) / (Bus No.)	1200 (30)	1200 (30)	1050 (30)
PLoss (KW)	35.599	25.186	18.011
QLoss (KVAr)	30.082	30.009	25.585
% Additional PLoss reduction	16.48385	14.078	12.7505
Total PLoss reduction	83.130%	88.060%	91.464%
Vmin (p.u) / Bus No.	0.97766 (33)	0.97732 (18)	0.9800 (33)
	CAPACITORS AT TWO OPTIMAL NODES		
Capacitor size (KVAr) / (Bus No.)	1050 (30) 450 (22)	1050 (30) 600 (8)	1050 (30) 750 (8)
PLoss (KW)	31.869	20.182	11.134
QLoss (KVAr)	26.649	25.629	17.878
% Additional PLoss reduction	18.252	16.45	16.01
Total PLoss reduction	84.90%	90.44%	94.72%
Vmin (p.u) / Bus No.	0.98281 (25)	0.98492 (32)	0.9896 (33)
	CAPACITORS AT THREE OPTIMAL NODES		
Capacitor size (KVAr) / (Bus No.)	1050 (30) 450 (22) 600 (24)	1050 (30) 600 (8) 300 (6)	900 (30) 750 (8) 300 (22)
PLoss (KW)	29.121	19.063	10.443
QLoss (KVAr)	24.93	24.736	17.365
% Additional PLoss reduction	19.5554	16.98	16.337
Total PLoss reduction	86.20%	90.97%	95.05%
Vmin (p.u) / Bus No.	0.98673 (25)	0.98685 (32)	0.99116 (18)
	CAPACITORS AT FOUR OPTIMAL NODES		
Capacitor size (KVAr) / (Bus No.)	900 (30) 300 (8) 450 (14) 450 (24)	750 (30) 600 (8) 300 (6) 450 (29)	1050 (30) 600 (8) 300 (4) 150 (33)
PLoss (KW)	28.672	18.662	10.075
QLoss (KVAr)	23.963	24.797	16.683
% Additional PLoss reduction	19.767	17.17	16.512
Total PLoss reduction	86.41%	91.16%	95.23%
Vmin (p.u)/ Bus No.	0.98705 (25)	0.98772 (32)	0.9922 (28)

Table 4. Performance of AGPSO in OCAP – 69 Bus system (Scenario 1)

Parameters	Case VI	Case VII	Case VIII
	CAPACITORS AT SINGLE OPTIMAL NODE		
Capacitor size (KVAr) / (Bus No.)	1200 (61)	900 (61)	1050 (61)
PLoss (KW)	28.657	28.508	14.847
QLoss (KVAr)	20.296	22.518	13.541
% Additional PLoss reduction	8.377	8.054	11.7065
Total PLoss reduction	87.261%	87.327%	93.404%
Vmin (p.u) / Bus No.	0.9693(65)	0.96896(62)	0.9831 (65)
	CAPACITORS AT TWO OPTIMAL NODES		
Capacitor size (KVAr) / (Bus No.)	1200 (61), 300 (64)	900 (61), 300 (64)	1050 (61) 300 (21)
PLoss (KW)	23.362	22.566	13.007
QLoss (KVAr)	16.446	18.319	11.869
% Additional PLoss reduction	10.731	10.694	12.5243
Total PLoss reduction	89.6146%	89.968%	94.218%
Vmin (p.u) / Bus No.	0.9737(63)	0.9736 (62)	0.9883 (65)
	CAPACITORS AT THREE OPTIMAL NODES		
Capacitor size (KVAr) / (Bus No.)	1200 (61) 300 (11) 300 (64)	900 (61) 300 (64) 450 (11)	1050 (61) 300 (21) 300 (11)
PLoss (KW)	21.727	20.836	11.371
QLoss (KVAr)	15.671	17.472	11.093
% Additional PLoss reduction	11.457	11.4635	13.2514
Total PLoss reduction	90.341%	90.7375%	94.9451%
Vmin (p.u) / Bus No.	0.9757(64)	0.9756 (62)	0.98859(65)
	CAPACITORS AT FOUR OPTIMAL NODES		
Capacitor size (KVAr) / (Bus No.)	1200 (61) 300 (11) 150 (17) 300 (64)	900 (61) 300 (64) 450 (11) 150 (18)	1050 (61) 300 (21) 300 (11) 450 (49)
PLoss (KW)	21.153	20.172	10.638
QLoss (KVAr)	15.111	16.843	9.307
% Additional PLoss reduction	11.7126	11.759	13.5773
Total PLoss reduction	90.5966%	91.033%	95.271%
Vmin (p.u)/ Bus No.	0.9768(63)	0.97883(62)	0.98931(65)

loss reduction achieved after case VII is between 8.9526% and 11.9366%. The total power loss reduction elevated to 93.0673%, 94.7757%, 95.933% and 96.0513% respectively. The bus voltage improvements after case VII are between 0.00378 p.u and 0.01065 p.u. Finally considering case VIII, optimal allocation and sizing of capacitors from single node to four nodes lead to an additional power loss reduction from 9.9169% to 11.746% and the total power loss reductions improved to 94.521%, 3%, 96.0276% and 96.3555% respectively. The improvement in bus voltages are between 0.004 and 0.00894 p.u.

Finally, it has been substantiated that the results obtained by the proposed method (AGPSO) are convincing and promising in achieving the significant additional power loss reduction by reactive power compensation. Fig. 5 and Fig. 6 display the node voltage obtained considering all the cases and scenario 1 & 2.

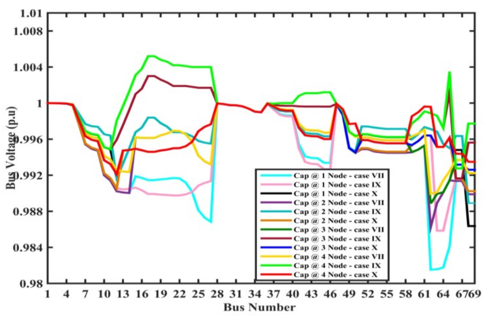

Fig. 5. Bus Voltage profile post capacitor placement – 33 Bus test system – Scenario 1

5. CONCLUSIONS

It is the responsibility of the DISCOs to identify the potential nodes for real and reactive power injections

Table 5. Performance of AGPSO in OCAP – 69 Bus system (Scenario 2)

Parameters	Case VI	Case VII	Case VIII
CAPACITORS AT SINGLE OPTIMAL NODE			
Capacitor size (KVAr) / (Bus No.)	1200 (61)	900 (61)	900 (61)
PLoss (KW)	17.563	15.595	12.325
QLoss (KVAr)	10.454	13.329	11.219
% Additional PLoss reduction	9.3728	8.9526	9.9169
Total PLoss reduction	92.1925%	93.0673%	94.521%
Vmin (p.u) / Bus No.	0.98532 (64)	0.98503 (62)	0.98686 (63)
CAPACITORS AT TWO OPTIMAL NODES			
Capacitor size (KVAr) / (Bus No.)	300 (11) 1050 (61)	300 (64) 900 (61)	300 (64) 900 (61)
PLoss (KW)	11.942	11.752	10.572
QLoss (KVAr)	12.475	10.895	9.6683
% Additional PLoss reduction	11.8716	10.661	10.696
Total PLoss reduction	94.6913%	94.7757%	95.3%
Vmin (p.u) / Bus No.	0.98871 (64)	0.98896 (62)	0.99023 (69)
CAPACITORS AT THREE OPTIMAL NODES			
Capacitor size (KVAr) / (Bus No.)	300 (27) 300 (49) 1050 (61)	450 (11) 300 (64) 900 (61)	300 (11) 300 (64) 900 (61)
PLoss (KW)	10.196	9.1489	8.9359
QLoss (KVAr)	9.5917	7.0832	8.892
% Additional PLoss reduction	12.6477	11.8183	11.4235
Total PLoss reduction	95.4674%	95.933%	96.0276%
Vmin (p.u) / Bus No.	0.99086 (64)	0.98952 (62)	0.9918 (69)
CAPACITORS AT FOUR OPTIMAL NODES			
Capacitor size (KVAr) / (Bus No.)	150 (18) 300 (49) 1050 (61) 300 (27)	900 (61) 450 (11) 300 (49) 300 (64)	900 (61) 300 (64) 300 (11) 450 (50)
PLoss (KW)	9.6505	8.8824	8.2148
QLoss (KVAr)	8.2593	6.7017	7.1309
% Additional PLoss reduction	12.8903	11.9366	11.746
Total PLoss reduction	95.71%	96.0513%	96.3555%
Vmin (p.u)/ Bus No.	0.99187 (64)	0.9919 (62)	0.99257 (69)

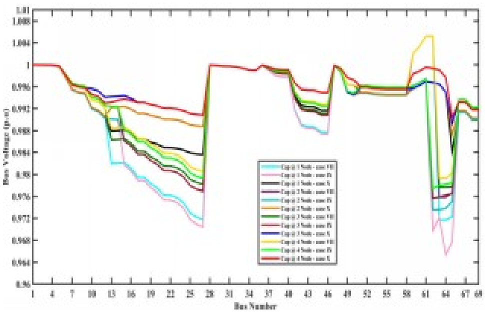

Fig. 6. Bus Voltage profile post capacitor placement – 33 Bus test system – Scenario 2

(DG / Capacitor) to minimize power loss. Integration of DGs and its total penetration are limited to minimum in order to avoid protection coordination issues, islanding problems, increase in real power loss etc. The proposed algorithm and methodology help effectively in finding optimal buses with appropriate capacities and optimal network structuring (NR) based on minimum power loss which is a great challenge for the DISCOs to manage the operational problems in DN. Taking into consideration the above issues, it is obvious that it is possible to inject real power to some extent, beyond which power loss reduction is possible only by installing capacitors at optimal nodes. The base paper (Srinivasan and Visalakshi, 2016) discussed the concept of real power injection at one and two optimal nodes with optimal network structuring.

Hence in this research study, a comprehensive analysis has been conducted to examine the additional power loss reduction by employing reactive power compensation which starts from a single node upto four nodes in single and two DG integrated optimal radial DN, to ascertain the impact of capacitors on additional power loss minimization under three different cases using AGPSO as optimization tool and also to demonstrate the supremacy of the proposed technique. Standard IEEE 33 and 69 bus test systems are used to confirm the efficacy of the proposed method.

It has been proved that allocation of capacitors from single node to four nodes in single and two DG integrated reconfigured radial DN yield maximum additional power loss reduction between 14% and 22% for 33 bus test system and between 8% and 13.5773% for 69 bus test system compared to (Srinivasan and Visalakshi, 2016) using the proposed technique. However the power loss reduction achieved under case VI, yield more power loss reduction than cases VII and VIII. From the simulation results, the maximum power loss reductions after cases VI to VIII are observed as 77% and 95% for 33 bus system and from 87% to 96.3% for 69 bus test system. Significant node voltage improvements have been achieved compared to (Srinivasan and Visalakshi, 2016). From the results, it has been proved that the performance of the developed technique is commendable in achieving maximum additional power loss reduction.

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Appendix A

ACI	After Capacitor Installation
BCI	Before capacitor Installation
MS	Main Source
NC	No. of nodes for capacitor placement
P_D, Q_D	Active and reactive power demand
P_{LOSS}	Active power loss in a particular branch
Q_{LOSS}	Reactive power loss in a particular branch
Q_{MS}	Total reactive power supplied by the Main Source
TB	Total No. of branches (TNB-1)
TNB	Total No. of Buses
TP_{LOSS}	Total active power loss
TQ_{LOSS}	Total reactive power loss
V_t^{max}	Minimum Voltage (0.95 p.u)
V_t^{max}	Maximum Voltage(1.05 p.u)
V_t	Voltage at t^{th} node
$Q_{c(t)}$	Capacitance of the Capacitor at t^{th} node