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Optimal Allocation of Capacitor Bank in Radial Distribution System for Loss Minimization and Voltage Profile Improvement

Milan Silwal [a], Shree Raj Shakya [b]

[a, b] *Department of Mechanical Engineering, Pulchowk Campus, IOE, TU, Nepal*
Corresponding Email: [a] silwalmilan9@gmail.com, [b] shreerajshakya@gmail.com

Abstract
This paper presents particle swarm optimization(PSO)to determine the optimal location and size of the capacitor bank in distribution system.Two stage procedure was implemented based on loss sensitivity index(LSI) and PSO.LSI was used to determine the optimal location while PSO is used to determine the optimal size of the capacitor bank.Load flow was carried out by using backward-forward sweep algorithm.The proposed procedure was applied to IEEE 34 and 69 bus system and on a real distribution system,i.e Parsa feeder,Chitwan.The result of IEEE 34 and 69 bus system was compared with previous publications.Simulation result shows there is significant loss reduction and voltage profile improvement after using capacitor bank in distribution system.

Keywords
Distribution System,Loss minimization,voltage profile,particle swarm optimization

1. Introduction

The distribution system is the part of the electric power system that provides the energy to the consumers . In 2019,distribution system loss of Nepal electricity authority(NEA) is 11.28% while the overall system loss is 15.32% [1].The distribution losses can be reduced by proper selection of distribution transformers, feeders, proper re-organization of distribution network, placing the shunt capacitor in appropriate places, and penetration of distributed generations at different point of distribution networks.

Capacitor banks are used in the distribution network for reactive power compensation to minimize the power loss, voltage regulation and capacity release. The extent to which loss is minimized and voltage improves depends upon the proper selection of the size of capacitor bank and the position at which it is located. The placement of random size of capacitor bank may lead to higher losses if placed. Furthermore, the optimum size of capacitor bank may not provide the optimum result i.e. minimum power loss if placed to different location.In order to maximize the benefits oriented from capacitor bank placement, the proper selection of the position and size is desirable.

Nojavan et. al (2014) developed solution methodology for optimal capacitor bank in radial distribution system based on mixed integer nonlinear programming approach that determine the optimal sitting and sizing of capacitors with an objective of reduction power loss and investment capacitor costs [2]. Sirjani (2010) presented the Harmony Search algorithm to solve the optimal capacitor placement problem. An effective and simple power flow method based on the backward/forward sweep power flow is also employed for the power flow simulations. The performance of the proposed HS algorithm is validated on the 9 and 34-bus radial distribution systems [3]. Das(2008) presented a genetic algorithm (GA) based fuzzy multi-objective approach for determining the optimum values of fixed and switched shunt capacitors to improve the voltage profile and maximize the net savings in a radial distribution system [4].

Gou et al (1999) studied the optimal capacitor allocation aimed to minimize the system losses and capacitor costs. This study also accounted for the voltage harmonic distortion brought about by the placement of capacitors [5].Muthukumar and Jayalalitha(2017) proposes a novel hybrid heuristic search algorithm based on Harmony search and particle artificial bee colony algorithm (HSA-PABC) for shunt capacitor placement problem.[6].El-fergany and Y. Abdelaziz(2014) presented cuckoo search optimization-based approach to allocate static shunt capacitors along radial distribution networks. The objective function was to minimise the system operating cost at different loading conditions and to improve the system voltage profile [7].Devabalaji et al(2015) proposed new integrated approach of Loss Sensitivity Factor (LSF) and Voltage Stability Index (VSI) determine the optimal location for installation of capacitor banks using Bacterial Foraging optimization algorithm (BFOA) The proposed method was applied on IEEE 34-bus and 85-bus radial distribution system with all possible load changes [8].The objective of this study is to determine optimal size and location of capacitor bank in the radial distribution system.

2. Methodology

The methodology followed in this study is summarized in flowchart depicted in Figure 1.

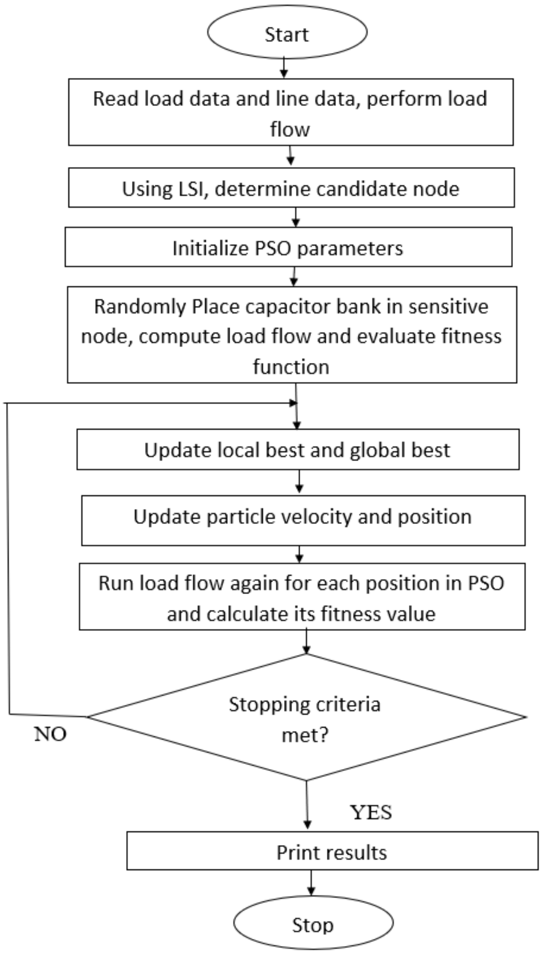

Figure 1: Flowchart of the optimization problem

Load data and line data of IEEE standard bus is obtained from literature review of earlier publications while that of Parsa feeder was obtained from Khaireni substation. An algorithm is developed to determine the loss sensitivity index and particle swarm algorithm for optimal allocation of capacitor bank in the radial distribution system. Load flow study is required to determine the voltage, current, phase angle of the system. Loss sensitivity index is required to select the candidate bus for the installation of capacitor bank. All the algorithm is simultaneously run so that optimum result is obtained.Furthermore,the results obtained from simulation is compared with the results of paper.

The objective function is to minimize the total cost which includes annual power losses and capacitor cost.

The power loss of the branch is calculated by line current I and branch resistance R as $P = I^2R$. The total power loss is evaluated by adding all the line losses

$$Total\ power\ loss = \sum_{i=1}^{b} P_i \tag{1}$$

Where, b is number of branches.

The power loss given by the load flow process is peak power loss. The average power loss is calculated by using loss load factor (LLF).

$$Average\ Loss = Peak\ Loss * LLF \tag{2}$$

Therefore, the average loss is calculated as the peak power loss multiplied by LLF. The average power loss when multiplied by factor of 8760 gives the annual energy loss. The total cost of energy lost is calculated as given by the following equation.

$$\begin{aligned} &Annual\ Total\ Power\ Loss\ Cost \\ &= LLF \times \text{Total Active Power Loss} \times \\ &\qquad Per\ Unit\ Energy\ Cost \times 8760 \end{aligned} \tag{3}$$

The cost of capacitor depends on the size of capacitor bank to be installed. Though cost of per unit size of capacitor varies from size to size i.e. per unit cost of capacitor of lower sized capacitor banks are more compared to per unit cost of large capacitor banks. The cost for of capacitor bank in the distribution network can be expressed as,

$$Annual\ Capacitor\ Cost = \frac{(k_c * Q_{VAR})}{(Life\ expectancy)} \tag{4}$$

Where, k_c is the unit cost of capacitor \$/kVAr,and life expectancy is the expected operation time of capacitor bank in year. Q_{VAR} is size of capacitor to be installed in kVAr.

The objective function is defined as,

$$\begin{aligned} &Minimize \\ &F = Annual\ Total\ Loss\ Cost \\ &\qquad + Annual\ Capacitor\ Cost \end{aligned} \tag{5}$$

The solution with the minimum value of objective function obtained after satisfying the constraints is the optimized solution . The optimized solution is that which gives the minimum system loss under voltage constraints with the size and bus number where the capacitor bank is to be placed.

2.1 Particle Swarm Optimization

Particle Swarm Optimization (PSO) is an intelligent optimization algorithm based on the Swarm Intelligence. It is based on a simple mathematical model, developed by Kennedy and Eberhart in 1995, to describe the social behavior of birds and fish. The model relies mostly on the basic principles of self-organization which is used to describe the dynamics of complex systems [9].

Suppose particle is in its current position .Each particle tries to modify its position by using following information.

- The current velocities
- The distance between the current position and the personal best
- The distance between the current position and the global best.

Initial algorithm of PSO defined by Eberhart and Kennedy mentioned below.Equation relates to velocity update .

$$\begin{aligned} V_x = V_x &+ 2 \times rand \times (pbestx - x) \\ &+ 2 \times rand \times (gbestx - x) \end{aligned} \tag{6}$$

Similarly,equation 2 corresponds to the position update of the particle.

$$x = x + V_x \tag{7}$$

Since initial version of PSO was not very effective in optimization problem, a modified PSO algorithm is developed by Shi and Eberhart in 1998.Furthermore, they suggested that inertia weight should be set to [0.9 1.2] and linearly time decreasing inertial weight could significantly enhance PSO performance [10]. Inertia weight(w) was introduced to the velocity update formula which becomes:

$$\begin{aligned} V_x = w \times V_x &+ c_1 \times r_1 \times (pbestx - x) \\ &+ c_2 \times r_2 \times (gbestx - x) \end{aligned} \tag{8}$$

Similarly,the equation to update the position of particle is :

$$x = x + V_x \tag{9}$$

In the equation 8,the first component of the equation is called the inertial weight.Second and the third terms are called the personal and the social influence term respectively.Large value of inertia weight(w) facilitates greater global search ability while smaller value facilitates greater local search ability.The term c_1 and c_2 are called the acceleration coefficients which represents the weights of the stochastic acceleration terms that pull each particle toward personal best(pBest) and global best(gBest).In many cases, c_1 and c_2 are set to 2.0.If c_1 is greater than c_2 ,then it helps greater global search ability while in reverse case it helps in greater local search ability.If c_1 and c_2 is equal to zero,particle keep flying at the current speed until they hit a boundary of the search space(assuming no inertia).If c_1 is greater than 0,and c_2 is equal to 0,all the particles are independent hill climbers.each particles finds the best position in its neighborhood by replacing the current best position if the new position is better.On the other hand if c_1 equals 0, and c_2 is greater than 0,the entire swarm is attracted towards a single point,global best. r_1 and r_2 are the uniformly distributed numbers in the range 0 to 1.

2.2 Backward Forward Sweep Algorithm

Consider a radial distribution system consisting of N nodes as shown in the figure 2 below.The load flow is carried out in following steps:

Step 1: Initialization of node voltages with voltage at each bus to $Vs\angle 0^0$.

Step 2: Iteration count Initialization k, for first iteration $k = 1$.

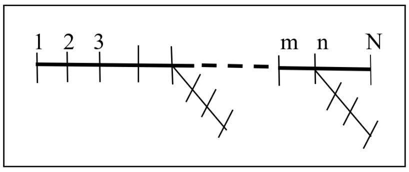

Figure 2: Typical Radial Distribution System

Step 3: Load current computation
Calculate load current (I_j) at Z_{th} bus during k^{th} iteration. The equation for current calculation is given by

$$I_j^{(k)} = \left(\frac{P_{Lj} + jQ_{Lj}}{V_j^{k-1}}) \right)^* \tag{10}$$

In this equation, voltage will be of $(k-1)^{th}$ iteration.

Step 4: Backward Sweep
In backward sweep, calculate the branch current (I_{mn}) between the buses m and n at k^{th} iteration. The branch current includes load current at n^{th} bus and summation of all the branch currents emanated from bus n.

Step 5: Forward Sweep
In forward sweep, the voltage at each bus is calculated. The voltage on the n^{th} bus will be the voltage at the m^{th} bus minus voltage drop in the m-n line. Line drop is calculated by multiplication of impedance and current of that line, whereas the m^{th} bus voltage is calculated prior to nth bus voltage calculation. The equation for bus voltage is given by

$$V_n^{(k)} = V_m^{(k)} - Z_{mn} I_{mn}^{(k)} \tag{11}$$

Step 6: Calculation of error
After the calculation of voltage at each bus by forward sweep process, calculation of error provides deviation in bus voltage at k^{th} iteration with respect to $(k-1)^{th}$ iteration. For example, error at bus m will be bus voltage at k^{th} iteration minus $(k-1)^{th}$ iteration. This process repeated from second bus to n^{th} bus.

$$e_j^{(k)} = |V_j^{(k)} - V_j^{(k-1)}| \tag{12}$$

Step 7: Calculation of maximum Error
In this step, calculate maximum error (e_{max}) among all the error, calculated between two consecutive iterations at each bus.

$$e_{max}^{(k)} = max(e_2^{(k)}, e_3^{(k)}, e_4^{(k)}, ..e_N^{(k)}) \tag{13}$$

Step 8: Tolerance
In this step, compare the maximum error with respect to tolerance value. The tolerance values is user define value. Generally, the region for tolerance value is 10^{-3} to 10^{-6}. The condition for converge is, if the maximum error becomes less than or equals to tolerance. Otherwise, proceed for next iteration $(k+1)^{th}$ i.e., go to step 3 and repeat the same process. Once the maximum error satisfies the convergence criteria then print the result.

2.3 Load Factor

The ratio of the average load during a designated period to the maximum load occurring at that time.

$$LF = \frac{Average\ load}{maximum\ load} \tag{14}$$

2.4 Load Loss Factor

The actual losses of the circuit is calculated by applying a factor to the total losses assuming maximum current to flow through that circuit during the whole period. This factor is called as load loss factor (LLF) which is defined as:

$$LLF = K * (LF) + (1-K) * LF * LF \tag{15}$$

The value of K varies from types of costumers[11].

2.5 Loss Sensitivity Index(LSI)

To identify the location for capacitor placement in distribution system, Loss Sensitivity Index have been used which is able to predict which bus will have the biggest loss reduction when a capacitor is placed. Therefore, these sensitive buses can serve as candidate buses for the capacitor placement. The estimation of these candidate buses basically helps in reduction of the search space for the optimization problem.

3. Case Studies

3.1 IEEE 34 Bus System

IEEE 34 bus radial distribution system is shown in Figure 3. The system has four laterals and branching occurs at node 3,6,7 and 10.The rated line voltage of the system is 11 kV and base of 100 MVA is used. The load data and line data of the bus is taken from [12]. Bus 1 acts as the substation where the voltage is assumed to be 1.00 pu. The total load of the system is 4636.5 kW and 2872.5 kVAr distributed at different buses.

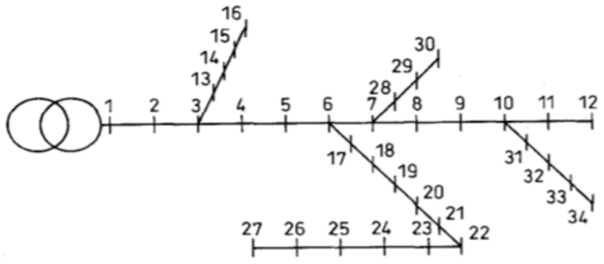

Figure 3: IEEE 34 Bus line diagram

3.2 IEEE 69 Bus Systems

It consists of 69-buses and 68 branches.Branching occurs at nodes 3,4,8,9 and 11. The standard system of 69 bus has 12.66 kV and 100 MVA base value. The single line diagram of the system is illustrated in figure 4. The data for this system was obtained from [4]. The total system rated load is of 1896 kW and 1347 kVAr.

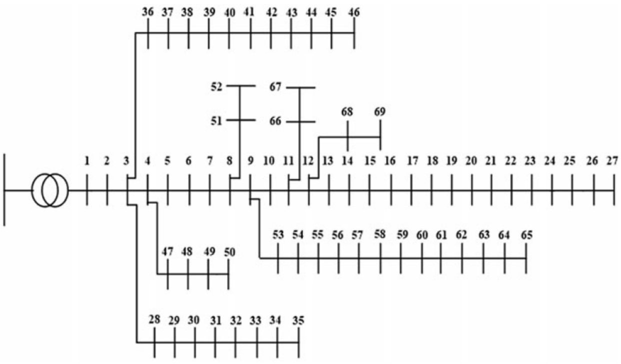

Figure 4: IEEE 69 Bus Line Diagram

3.3 53 Bus Parsa Feeder

A Parsa feeder is a radial distribution feeder that consists of 72 transformers connected into 11 kV primary distribution system. This system has been modified to 53 bus system after load on transformer located within 100-meter distance lumped to the single node. The total installed capacity of transformer is 9500 kVA and the substation operates at 0.8 lag power factor. The peak load of the system in 2019 was 9504 kW on July 16. Mostly high load occurs in summer season while in winter the load is comparatively low. The average load of the system is 4805.51 kW. Altogether there are 10 branches in the feeder. Dog conductor has been used in the main feeder while rabbit conductor was used in the lateral feeder. Main feeder comprises bus number 1 to 23 which can be seen in the single line diagram below. Bus 1 is the substation while other buses are the load bus.

The price of electricity was considered $761.73 kW-year. Similarly,loss load factor is calculated 0.3056 for this system.In this study,the capacitor size in the range between 150 kVAr and 1200 kVAr with the step size of 150 kVAr is considered.

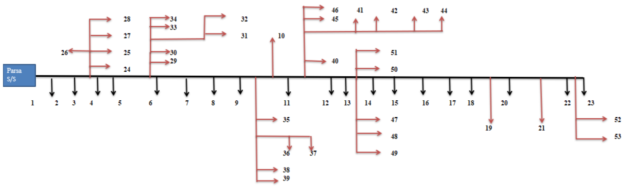

Figure 5: single line diagram of Parsa Feeder

Regarding the parameter selection of PSO,both the acceleration coefficients c_1 and c_2 was selected 2.0.Providing same value of c_1 and c_2 means that particle can have the same capacity of global search and local search.The swarm population was selected 100 and maximum iteration was 2000.Increasing the swarm population and maximum iteration count increases the computation time but better solution can be obtained.Similarly the value of inertial weight(w) was considered 1 .In the same way,the maximum and minimum unit size of capacitor bank was considered 1200 kVAr and 250 kVAr which varies with step size of 150 kVAr.The price of electricity was assumed $761.73 kW-year.Similarly,loss load factor was calculated 0.3056 for this system.

4. Result and Discussion

The algorithm was implemented by coding on MATLAB (Matrix Laboratory), R2016a, multi-paradigm numerical computing environment and eighth-generation programming language and executed on Intel Core i-7, 1.8 Giga Hertz (GHz) personal computer with 12 Giga Byte (GB) RAM. The proposed method for optimal capacitor allocation for loss reduction was tested in the IEEE standard 34 bus,IEEE 69 bus and in the Parsa feeder.

4.1 IEEE 34 Bus Systems

The load flow of the system was carried out using backward/forward sweep algorithm. The voltage profile of the system has been represented in the figure 6. The least value of voltage was at bus number

27 which is 0.94171 pu. In the uncompensated system, the annual power loss was obtained 221.6772 kW. The voltage profile gradually decreases from bus 1 to bus 12 because bus 12 is the terminal node of the main feeder but voltage at bus number 13 is comparable than that of node 3 because node 13 is branches out from node 3.In the same way, voltage at bus number 17 is comparable bus number 6 because node number 17 branches out from node number 6.

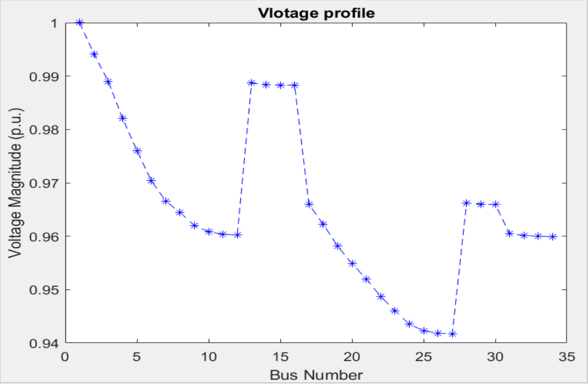

Figure 6: Voltage profile without compensation

The simulation result shows,the optimal location of capacitor bank was found at nodes 18,22,24 and 9.A total of 2550kVAr capacitor bank was suggested after simulation.The active power loss decreased to 159.86kW after compensation which corresponds to 29.9% loss reduction. Also the minimum voltage of the system rose to 0.95062 at bus 27.

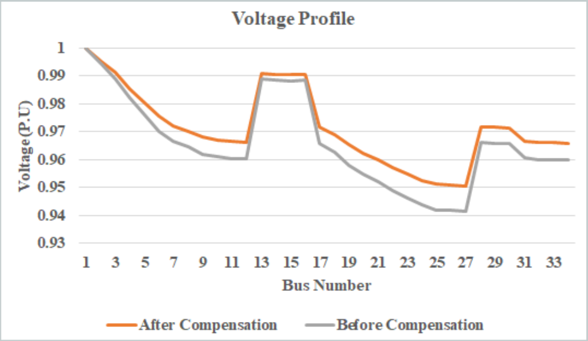

Figure 7: Voltage profile after compensation

Comparing the results with earlier publications,it was found that the proposed method provided better results.Active power loss was minimum using this method.Total loss using mixed integer non linear programming method was 162.9 kW while that using bacterial foraging optimization algorithm loss was 160.6 kW.

Table 1: Comparison with other methods

Parameters	Uncompensated	MINP [2]	BFOA [8]	Proposed method-PSO
Total losses (kW)	221.6772	162.9	160.6	159.8739
Optimal location Bus no size	-	4 300 10 600 14 100 18 500 22 300 27 1000	10 625 20 940 25 610	17 750 23 600 9 750 25 450
Cumulative size in kVAr	-	2800	2175	2550
Vmin (pu) at Bus No.	0.94171 at 27	0.9521 at 27	0.9499 at 27	0.9505 at 27

4.2 IEEE 69 Bus Systems

The load flow of the system was carried out using backward/forward sweep algorithm. The voltage profile of the system after load flow has been illustrated in the figure 9. The value of voltage was least at bus number 65 which is 0.90921 pu. In this uncompensated system, the power loss was 225.338 kW.The voltage profile of bus 3 and 36,3 and 28,9 and 53,8 and 51,11 and 66 is similar because of branching which can be seen clearly from the single line diagram of 69 bus system represented in figure 4 .The voltage profile of the uncompensated system is portrayed in figure 8.

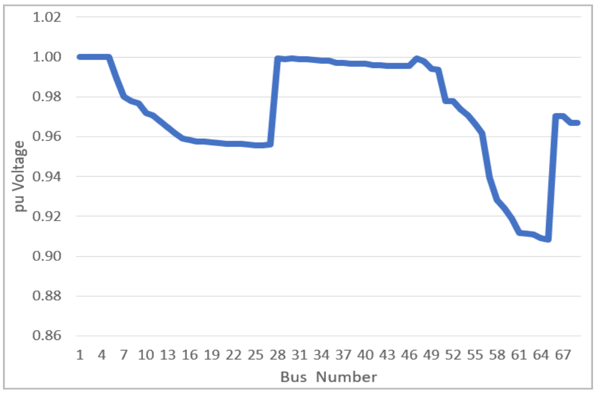

Figure 8: voltage profile of the uncompensated 69 bus system

After simulation it was found that,the optimal location of capacitor bank was found at nodes 7,21 and 62.The optimal sizes in this locations was calculated using PSO.At bus number 7,21 and 62, 300kVAr,150kVAr and 750kVAr capacitor bank was allocated respectively whose cumulative sum was 1200 kVAr .The active power loss decreased from 225.338 kW to 146.8644 kW after compensation which corresponds to 42.48% loss reduction.Similarly,there was significant improvement in the lowest value of voltage which rose from 0.90921 pu before compensation to 0.93219 pu after compensation. The minimum system voltage occurred at bus number 65.The voltage profile of the compensated and uncompensated IEEE 69 bus system is illustrated in the figure 7.

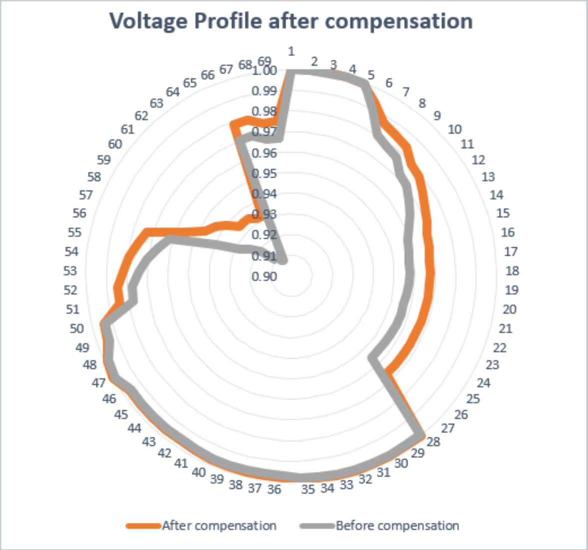

Figure 9: Voltage profile after compensation

Table 2: Comparison of the obtained results

Parameters	Uncompensated	FGA [4]	CSA [7]	HAS-PABC [6]	Proposed method-PSO
Total losses (kW)	225.338	156.64	148	147.74	146.864
Optimal location #Bus No. Size	-	#61 700 #64 800 #59 100	#62 250 #21 1450	#61 1150 #18 250	#7 300 #21 150 # 62 750
Optimal size in kVAr	-	1600	1700	1400	1200
Vmin (pu) at	0.90921, at 65	0.9369 at 65	0.93 at 65	0.9288 at 27	0.9321 at 65

The result obtained after the simulation was further compared with other papers.It was found this method provided superior performance in terms of loss reduction and voltage profile improvement.

4.3 53 Bus Parsa Feeder

The load flow of the system was carried out using backward/forward sweep algorithm. The voltage profile of the system after load flow is represented in the figure 12. The value of voltage is least at bus number 53 which is 0.7421 pu.As seen from the graph of the system,the voltage profile is in decreasing pattern from bus 1 to 23.This is the main bus of the system.Voltage profile is in decreasing pattern in main bus because voltage at bus number 1 is 1 p.u and due to impedance ,voltage decreases. Voltage at bus number 24 rises and nearly equal to bus number 3 which is 0.96 p.u.This is because branching occurs at bus number 3 which is connected to bus number 24.Similarly voltage at bus number 22 is 0.743 p.u which is nearly equal to bus number 52 because branching occurred from node 22 to 52.

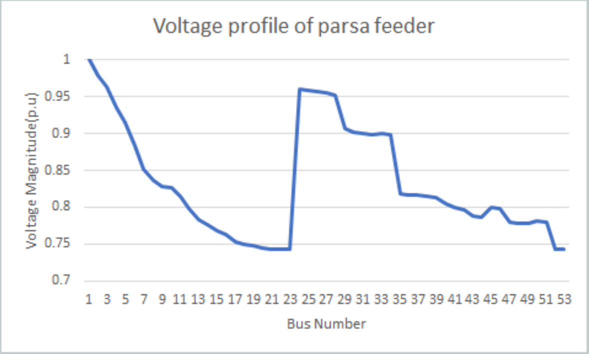

Figure 10: Voltage profile of Parsa Feeder without compensation

After simulation in MATLAB,total capacitor bank of size 4950kVAr is obtained in 8 different location shown in the table 1.

Table 3: Bus Number and capacitor size

SN	Bus Number	Size of capacitor(kVAr)
1	4	900
2	7	600
3	12	1200
4	17	1200
5	36	150
6	30	300
7	41	300
8	26	300
	Total	4950

After capacitor bank placement in the respective buses,the voltage profile increases which is illustrated in the figure 11.

Life expectancy and cost per kVAr of of the capacitor bank was considered 10 years and $5 respectively.So the annual cost of 4950 kVAr capacitor is $2475.Similarly electrical power loss after capacitor

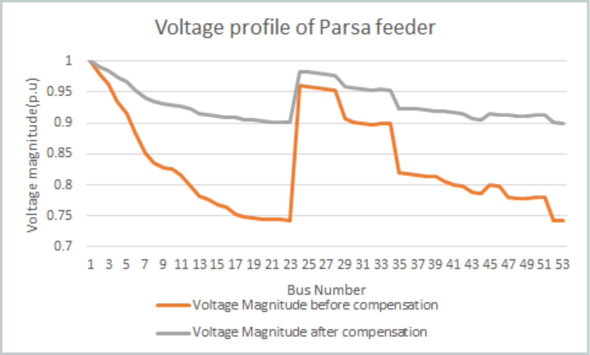

Figure 11: Voltage profile of Parsa feeder after capacitor placement

placement reduced from 1473.1654 kW to 804.147 kW which accounts net savings of 669.02 kW.This accounts to 45.41% power saved in compensated system when compared to the base case.This is the power saved during peak load period.The average power saved is obtained by multiplying the peak power saved by loss load factor,LLF=0.3056,so the net savings of 204.45 kW was obtained.Considering the price of electricity $761.73 kW-year, net annual value of electricity saved was $155,738.Deducting the savings from the annual cost of the capacitor bank,the net annual savings is $ 153,263.

Table 4: Calculation of Parsa feeder after capacitor placement

Parameters	Before Compensation	After Compensation
Minimum voltage(V)	0.7421, # 53	0.90011, # 53
Active power loss (KW)	1473.1654	804.1479
Total power saved (KW)	-	669.02
Price of electricity (KW-year) in $	761.734	761.734
Annual savings of Electricity compared to base case ($)	-	509,615
Total annual saving considering LLF=0.3056	-	155,738
Total size of capacitor bank(kVAr)	-	4950
Capacitor price per year ($)	-	2475
Net annual savings ($)		153,263

5. Conclusion

This paper presents the methodology for the optimal siting and sizing the capacitor bank in radial distribution system using particle swarm optimization(PSO).After compensation using capacitor bank,the peak power loss of IEEE 34 bus, IEEE 69 bus and Parsa feeder decreased by 29.9%,42.48% and 45.41% respectively.Comparing the obtained results with the earlier publication,it was found that this method provides superior results.Furthermore,it was found that significant loss reduction and better voltage profile was obtained after the installing capacitor bank in the radial distribution system.Therefore, the proposed procedure represented a potential tool to reduce the system loss and improve power quality of the utilities.Thus capacitors allocation aids in minimizing operating expenses and allow the utilities to serve new loads and customers with minimum system investment.

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