Optimal capacitor allocation for minimizing cost of energy loss in active distribution network with different load levels

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ABSTRACT

This paper proposes an effective technique to allocate a shunt capacitor using a meta-heuristic optimization-approach for minimizing the cost of energy losses. Particle swarm optimization (PSO) algorithm incorporated with MATPOWER is trained for minimizing the targeted function of the optical capacitor placement problem. The 115-node active distribution network supplied by MESC in the Mandalay distribution area is applied as a scenario. The results including active power loss and system energy loss, size and location of the optimized capacitor, voltage profiles, and the cost of energy loss are attained and analyzed. The simulations results revealed that the optimal allocation of the capacitor provides a significant reduction in the cost of energy losses as well as improvement in voltage profile with compensation of reactive power.

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1. INTRODUCTION

The shunt capacitor installation in a radial power distribution system has become significant research in power system planning. For advancing power flow control and enhancement of power factor, managing voltage profile, reducing active power loss and energy loss in the network, the shunt capacitor injection on the radial feeder is presently applied. In that case, it is necessary to consider economic criteria in the installation of the capacitor to get the best design procedure.

Dealing with the optimal capacitor placement (OCP) problem and sizing in the radial distribution network, many algorithms and techniques are addressed [1]–[4]. In literature, different researchers have introduced different methods considering different fitness functions including minimization of power losses, reduction in installation cost, and improvement in voltage profile, lessen the burden on existing lines as well as maximizing system stability, and others.

In earlier stages, the researchers proposed the analytical procedures [5], [6] because of the computing burdens and lack of resources. After that, numerical programming [7], heuristics techniques [8], and artificial intelligent methods [9] have been progressed in OCP research. Because of making a high-quality solution within short calculation-time and stable convergence characteristics, particle swarm optimization (PSO) approaches [10] have been employed on capacitor installation research in distribution networks. The [7]–[10], the major focus is on the minimum power losses of the system and the improvement of the bus voltage regulation.

From the literature review, it is observed that the application of the PSO algorithm targeting with the cost of energy loss, evaluating with daily load curves, has not been discovered in previous work. Besides, the active practical distribution network is rarely tested for OCP. It motivates that the practical case study should be tested for the optimal allocation for different load levels.

Therefore, the present research mainly focuses on a case study for OCP for practical distribution network considering the daily load curve segmented by four different load levels. In this paper, the capacitor sizes are firstly evaluated by using the analytical method, and these values are applied as initiators in the optimization process. The OCP is implemented by using the PSO algorithm for minimization of cost of energy loss of a practical 115-bus, 4-feeder radial distribution network of MESC service area, Mandalay, Myanmar.

The paper is organized as follows. Section 2 designates the methodology and problem formulation of OCP. The PSO algorithm for OCP is discussed in section 3. Section 4 grants the practical case study network information while the simulated results of the scenario with discussions are demonstrated in section 5. Finally, the main conclusion is drawn in section 6.

2. PROBLEM FORMULATION

In this paper, the OCP is implemented with the daily load curve supporting multi-segments to minimize the cost of energy losses. The mathematical formulations for OCP are discussed in the following sections.

2.1. Objective function

The main objective function, f, of OCP, in this research, is to minimize the cost of energy losses summing up the cost of energy losses at each load considering varying load conditions.

$$Minimize\ f = K_e \sum_D \sum_{j=1}^{nl} \left(P_{loss_j}.T_j\right) \tag{1}$$

Where K_e is the cost per unit of energy losses (\$/MWh) of the system, D is the number of days in which the savings are evaluated, $P_{loss,j}$ is the real loss of power in the distribution network concerning the load level, j, nl is the number of load levels and T_j is the time interval for respective load intervals.

2.2. Constraints

The power balanced equations for each bus are considered as equality constraints while the technical limitations are considered as inequality constraints [11]. The constraints that need to be restricted are itemized below:

- Operational constraints on bus bar voltage

$$V_i^{min|V_i|_i^{max}} \tag{2}$$

where, V_i is the voltage magnitude of bus i, and in radial power systems, V_{min}= 0.9 and V_{max}=1.1 [1], [12], [13].

- Constraints on reactive power compensation in network

$$Q_{Ci} \leq 0.75 \sum_{i=1}^{n} Q_{Li} \tag{3}$$

where, Q_{Ci} is the allowable capacitor size at bus i and Q_{Li} is the reactive power demand on each bus.

- Limitations on line flow (LF):

$$LF_k < LF_{k(max)} \tag{4}$$

where, LF_k is the power flow in the k^{th} line and $LF_{k(max)}$ is the maximum power flow allowed.

- Constraint on capacitor size

$$QC_{C,max_{C,min}} \tag{5}$$

2.3. Fitness function

Since the OCP is a non-linear optimization problem, it is required to consider a fitness function for both the security and economy of the system. The fitness function, F can be formulated as the penalty function added to the target function. In this research, it can be stated as (6):

$$F = f + \sum_{i=1}^{\sum^{2}\sum_{i=1}^{\sum^{2}} \lambda_{Q_{Ci}}\left(Q_{Ci} - Q_{Ci}^{lim}()\right)} \lambda_{vi}\left(V_i - V_i^{lim}()\right) \quad (6)$$

where, λ_{vi} and λ_{Qci} are the penalty factors for voltage limit and reactive power compensation limit, respectively. In (6), the allowable maximum and minimum limits of voltage magnitude and amount of reactive power injected by the capacitor are

$$V_i^{lim} \begin{cases} V_i^{min}, & V_i < V_i^{min} \\ V_i^{max}, & V_i > V_i^{max} \end{cases} \quad (7)$$

$$Q_{Ci}^{lim} \begin{cases} Q_{Ci}^{min}, & Q_{Ci} < Q_{Ci}^{min} \\ Q_{Ci}^{max}, & Q_{Ci} > Q_{Ci}^{max} \end{cases} \quad (8)$$

3. OCP IMPLEMENTATION USING PSO

3.1. Analytical procedure for initial capacitor size

The capacitor size is one of the control variables to be considered in OCP. Before the optimization process, the initial capacitor sizing for each bus except the station bus is evaluated using the analytical approach. According to [6], [14], based on the load flow results, the branch current between the bus 'i' and 'k' is evaluated by:

$$I_{ik} = \frac{P_{ik} - jQ_{ik}}{V_i} \quad (9)$$

The total power loss (TPL) due to active (a) and reactive (r) components of current in the distribution lines is

$$TPL = \sum_{ik=1}^{n}\left(|I_{ik}^{a}|^2 + |I_{ik}^{r}|^2\right) R_{ik} \quad (10)$$

For reactive power compensation, the reactive current I_C is drawn by the injected capacitor. For a radial network, it changes just only on the reactive component of the branch current set α, and it does not affect the current of other branches. Therefore, the new reactive current can be designed by [14].

$$I_{ik}^{new} = I_{ik}^{r} + D_{ik} I_C \quad (11)$$

Where D_{ik} is considered as 1 if branch $(i, k) \in \alpha$, 0 for otherwise. After capacitor placement, the compensated power loss is maximized and it can be expressed in the mathematical formula as (12).

$$TPL_r^{com} = \sum_{ik=1}^{n}\left(I_{ik}^{new}\right)^2 R_{ik} = \sum_{ik=1}^{n}\left(I_{ik}^{r} + D_{ik} I_C\right)^2 R_{ik} \quad (12)$$

The total power loss saving (TLS) can be evaluated as

$$TLS = TPL_r - TPL_r^{com} = \sum_{ik=1}^{n}\left(|I_{ik}^{r}|^2\right) R_{ik} - \sum_{ik=1}^{n}\left(I_{ik}^{r} + D_{ik} I_C\right)^2 R_{ik} \quad (13)$$

From the TLS equation, the capacitor current, I_C that provides the maximum loss saving can be get by differentiating TLS for I_C and equal to zero. Then,

$$I_C = \frac{1}{\sum_{ik\in\alpha}^{n} R_{ik}}\left(-\sum_{ik\in\alpha}^{n} I_{ik}^{r} R_{ik}\right) \quad (14)$$

assuming that there is no significant change in the voltage after capacitor placement, due to change in the active component of load current at respective buses, the initial capacitor size at candidate bus can be stated as (15).

$$Q_C = V_m I_C \quad (15)$$

Based on [13], [14], the quantity of reactive power injection should be within their feasible limits. And also, the total reactive power injection must be less than or equal to the total reactive load demand [4], [7] and that must be used as inequality constraints as in (3).

3.2. Basic concept of PSO

Since 1995, Kennedy and Eberhart proposed the PSO algorithm [15] based on the computational simulations of the movements of animals like birds and fishes [10]. E. O. Wilson explained the linkage of these simulations [16] for optimization problems. In PSO techniques, particles change their positions and velocities by flying around a multi-dimensional search set which is linked with the simplest solution (fitness). In each time step, the general best value (pbest for private best) and its location obtained (gbest for global best) are tracked by rushing the velocity of each particle within the population, and also the acceleration is weighted by random standings.

The brief practice to implement the global sort of PSO is prearranged by the subsequent phases [10]:

- Initialization: Initialize a population of particles with random positions ad velocities.
- Evaluation: Estimate the fitness value of every particle.
- Comparison 1: Compare each particle's fitness with the particle's pbest. If this value is better than pbest, then state the pbest equaling to the current one following the current position.
- Comparison 2: Compare the fitness with the overall previous finest. If the recent value is improved than gbest, then reorganize gbest to the current directory and value.
- Updating: Update the rate and position of each particle by using the following calculations.

$$v_{ij}^{k+1} = w^k v_{ij}^k + c_1 r_1 (pbest_{ij} - x_{ij}^k) + c_2 r_2 (gbest_{ij} - x_{ij}^k) \tag{16}$$

$$x_{ij}^{k+1} = x_{ij}^k + \Delta t . v_{ij}^{k+1} \tag{17}$$

where, c_1, c_2 are cognitive and social component factors, w is the inertia weight parameter, and r_1, r_2 are two random numbers produced in the range {0, 1}, respectively. In (17), the position is restructured in line with the previous situation and velocity, as Δt=1.

The weighting function, w of a particle is given by

$$w^k = w_{max} - \left(\frac{w_{max} - w_{min}}{iter_{max}}\right) \tag{18}$$

where, w_{max} and w_{min} are the initial and final inertia weights, and $iter_{max}$ is the maximum number of iteration and $iter$ is the current number of iterations, respectively.

- Stopping: Go back to Step 2 until the stopping standard is met.

3.3. Strategy implementation of PSO algorithm incorporated with MATPOWER

This paper provides an optimal algorithm for OCP in the active distribution network. The primary computational work of the proposed approach is mainly based on power loss calculation, which is completed using MATPOWER [17]. It is a simulation tool for researchers easy to use and modify. It also supports for optimal process and state variable initializations [18]–[20]. Therefore, MATPOWER is incorporated in PSO algorithm calculations to support power loss calculation [21] and bus voltage profile evaluation, calling the simulation function "runpf." The OCP is determined based on the load demand curve of the system. In practice, consumer loads of networks vary with time over a wide range. Therefore, daily load curves are considered to define the operational program of shunt capacitor placement. In this work, a typical load curve with four different load levels is taken into account to estimate the average load demand profile of the test system. Therefore, four different system information data files are scripted initially in MATPOWER casefiles. In each case file, the range of voltage magnitude is set from 0.9 p.u to 1.1 p.u while the shunt var limit is 0.001 MVAr to 1.05 MVAr, respectively.

The comprehensive flowchart of the proposed PSO technique for OCP considering four-segment load curves to evaluate the energy loss is depicted in Figure 1. In this figure, a step-by-step procedure to optimize the capacitor allocation is demonstrated. These steps are intended for one candidate bus selection with the target of cost of energy loss minimization. To evaluate the power loss and voltage profile through the Newton load flow solver, MATPOWER toolbox is incorporated during the optimization process. In each step of optimization (particles of PSO), the load flow solver is called upon as a function and it is evaluated the energy loss in each iteration of the optimization algorithm. In the program setting, the parameters of PSO should be selected to seek out the global solution as well as to increase the computational complexity. The initialization of PSO parameters that require to be tuned for assessing the objective function is tabulated as basic parameters in Table 1.

As explained in section 3.1, the value of randomly generated numbers is within the range of {0, 1} to randomly weigh the social and cognitive behaviors meanwhile the stopping standard is touched to 100 times. To keep increasing until approaching infinity in the optimization process, the penalty multipliers for bus voltage, λ_{Vi}, and shunt compensation, λ_{Qc} are assigned big numbers with 25,500 and 10,000, respectively.

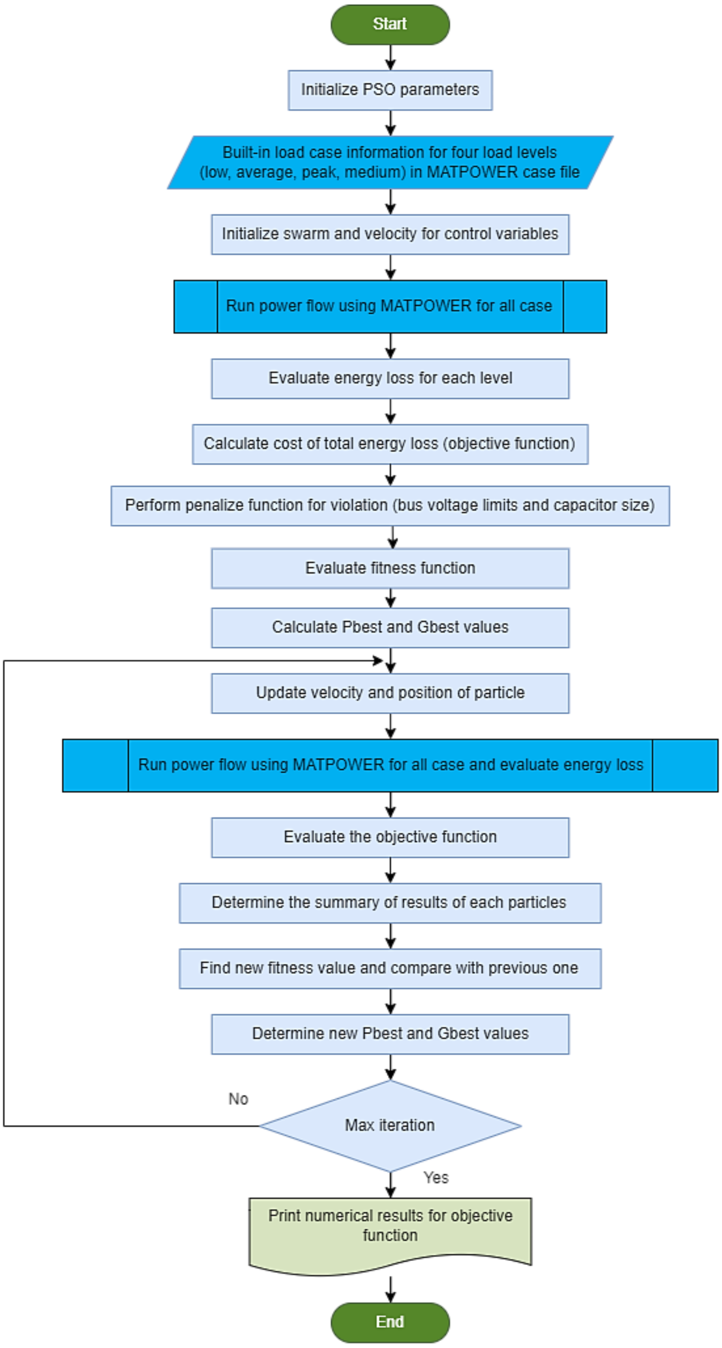

Figure 1. Flowchart of the proposed method for solving OCP

Table 1. Basic parameters of PSO

Sr. No.	Parameters	Value
1	Population size	40
2	Maximum inertia weight	0.9
3	Minimum inertia weight	0.4
4	Acceleration constants	[2.05, 2.05]
5	Maximum number of iterations	100
6	Random number	[0, 1]

4. CASE STUDY NETWORK

To validate the performance of the proposed methodology, the active distribution network of the Mandalay distribution area in Myanmar is employed. The scenario network [22] is described in Figure 2.

There are four feeders in the active network which distribute to the consumers. The system consists of 115 buses, 4 radial lines, 114 branches, and 102 load points, and also the rated capacity is 20 MVA.

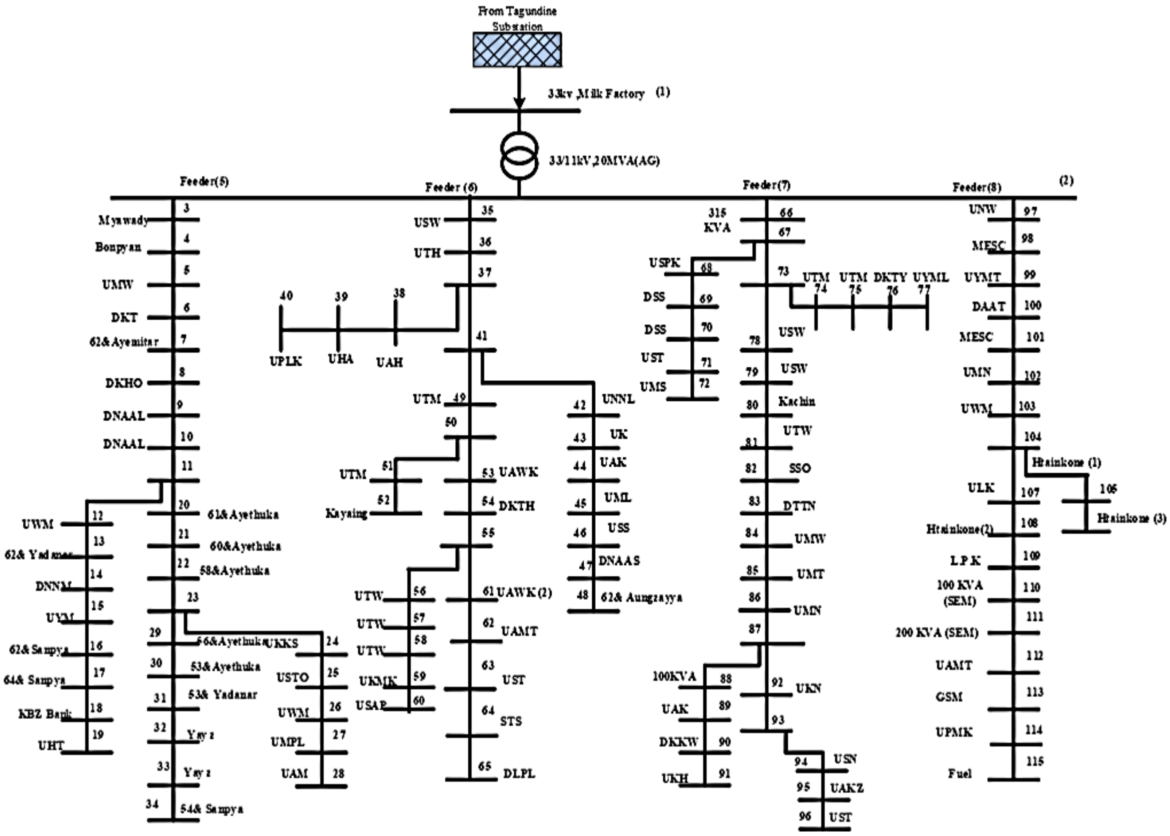

Figure 2. 115-bus system of Mandalay distribution area

To examine energy loss, the load variation in the system for a given period are taken under consideration. Based on the monthly load reports of September 2018 through August 2020 [23], the typical daily load curve is considered, eventually, taken at substation bus. The load profile is segmented into four intervals (L1-L4) based on system average mode condition during the loads are assumed to be constant during the time interval. The prominent load data during the whole day (24-hour) are summarized hourly and plotted on a graph. The typical load duration curve of the case study network is shown in Figure 3.

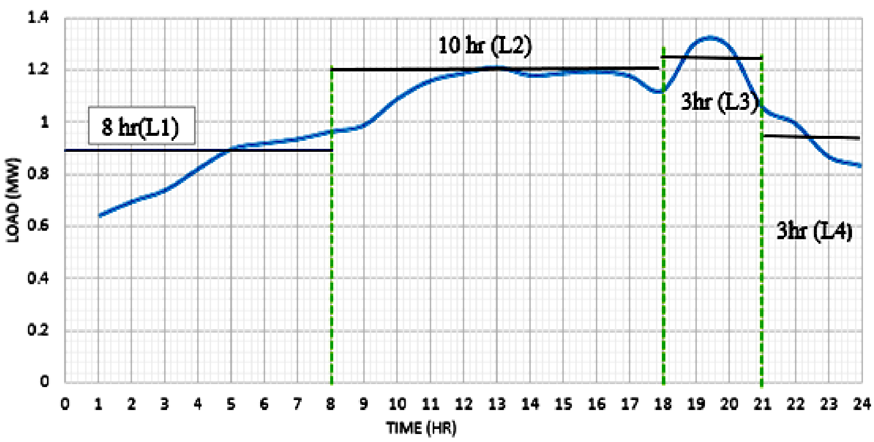

Figure 3. Typical load curve of the test system

For research purposes, the maximum demand of the system is considered as the base case, reference load level. The total time for study is related to one year of system operation and the energy price is taken to be considered as 0.065 $/MWh [24], [25]. The load demand, load-level factor, and the corresponding period of every load level are recorded in Table 2. The initial power flow solutions of base case and different load level cases are carried out and recorded. These parameters are applied to evaluate the initial capacitor sizing and to compare with the compensated results.

Table 2. Load levels 114-bus test system analysis

Load level	Level 1	Level 2	Level 3	Level 4
Total load (MW)	8.978	12.111	13.044	10.606
Load factor (p.u)	0.741	1.0	1.077	0.875
Time (h)	8	10	3	3

5. RESULTS AND DISCUSSION

In this section, the consequences of optimal size and site allocation using the proposed technique will be presented. Firstly, the analytical results for capacitor initial sizing will be explained, and followed by optimization results. The performance investigation of OCP also will be established. Finally, the OCP results will be compared and verified with the loss sensitivity factor (LSF) approach [1], [13] for capacitor allocation.

5.1. Analytical results for initial capacitor size

In this work, the initial load flow with the Newton load flow solver of MATPOWER is done to estimate the initial capacitor size at an allied bus. The procedure described in section 3.1 was employed. According to the results, the maximum rating of capacitor size is found at bus 2 with 0.4246 MVAr while the minimum is at bus 34 with 0.3441 MVAr, individually. These capacitor sizes obtained from the analytical approach were prepared as start-up sizings during the optimization process. The respective capacitor sizings are injected on each candidate bus and the different case files are implemented in M-file for four different load levels.

5.2. Numerical results for minimizing the cost of energy loss

The operation of the proposed strategy is done using intel®core™ i7-4770 CPU, 3.40 GHz with 4 GB RAM computer. In the optimization process, the capacitor sizes are taken into account as continuous variables starting with initial values of analytical results. The total 114 candidate casefiles (except substation bus) with four different load segments are supported in the optimization process. The convergence curve of OCP for one candidate solution (@case94) is given in Figure 4. In the respective profile summary, the optimized capacitor size at the affiliated bus for the cost of energy loss minimization, respective voltage profiles are principally recorded and compared.

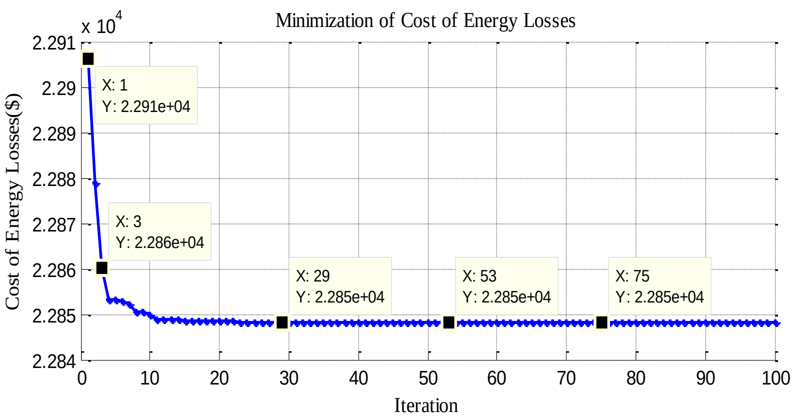

Figure 4. Minimization of cost of energy loss with capacitor

One of the recorded profile summaries is demonstrated in Figure 5. It can be seen from the figure that the "runpf" function is called upon 16160 times to compute the power flow solution getting the active power loss during the optimization process. It is shown that the PSO is well incorporated with MATPOWER and all of the four different load segments are well evaluated to induce the optimal solution for capacitor placement.

Profile Summary

Generated 07-Oct-2020 14:59:09 using cpu time.

Function Name	Calls	Total Time	Self Time*	Total Time Plot (dark band = self time)
energycostbus94of4load	1	991.697 s	19.608 s	
runpf	16160	909.795 s	30.648 s	
mpoption	16160	624.363 s	0.818 s	
mpoption>mpoption_default	16160	623.263 s	600.637 s	
printpf	16160	184.880 s	162.632 s	
savecase	16160	46.659 s	40.749 s	
newtonpf	16160	33.130 s	27.558 s	
isload	3781440	18.356 s	6.977 s	
idx_gen	3910720	12.743 s	12.743 s	
ext2int	16160	12.354 s	11.756 s	
nested_struct_copy	193920	11.431 s	10.713 s	
get_losses	48480	10.725 s	7.858 s	
loadcase	16164	8.673 s	6.660 s	
num2str	141400	8.177 s	3.965 s	
dSbus_dV	64640	5.026 s	5.026 s	

Figure 5. Profile summary of CPU time for PSO (@case94)

The optimization results associated with the cost of energy losses at each bus are investigated and compared to induce the optimal one. The optimal shunt capacitor sizes compared with initial sizes are demonstrated as a bar-chart in Figure 6. It can be seen from the figure that the optimal sizes are greater in values than that of initial cases and all are satisfied with predefined constraints. According to the results, the optimal sizes are between 0.573 MVAr @ bus 2 and 0.4764 MVAr @ bus 112. Accordingly, the obtained results of the cost of energy losses are compared and analyzed. The result summary of the cost minimization for each bus is demonstrated in Figure 7. In comparison results, the lowest value of the cost of energy losses is observed in bus 94 with the optimal size of 0.564 MVAr. Therefore, bus 94 is identified as the optimal location for the capacitor in the practical network.

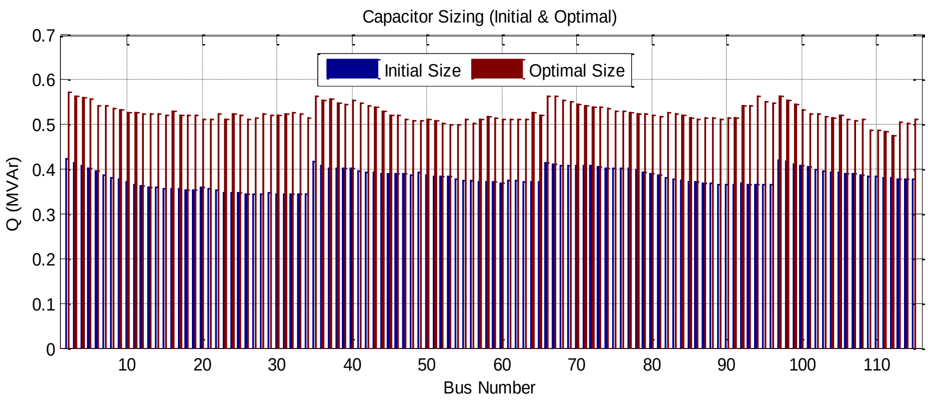

Figure 6. Comparison of initial and optimal capacitor sizes at allied buses

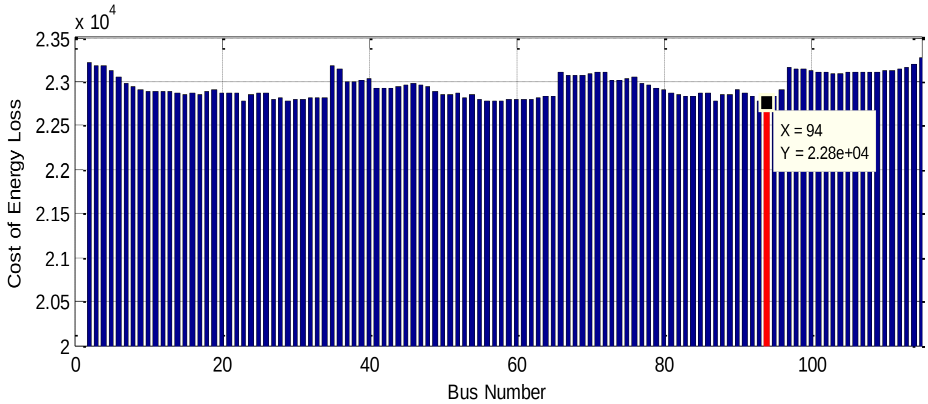

Figure 7. Comparison of cost of energy loss

5.3. Performance analysis on OCP

Based on the optimal results, the effect of loss reduction to capacitor placement, the respective voltage profiles, and the cost of energy loss impact is studied. The active power loss reduction for the four-segment load curve is summarized in Table 3. It can be found that the power loss reduction on different load levels is decreased obviously. Comparing with the base case and the initial size injection, the optimal capacitor placement with optimized size gets superior upshots in loss reduction than the two other cases in all load levels.

Table 3. Effect of loss reduction to capacitor placement

Load Level	Total active power losses (MW)			% Reduction in power losses		
	Base case	Initial size	Optimal size	Base case	Initial size	Optimal size
L1	0.841	0.812	0.75	-	3.448	10.82
L2	1.496	1.4584	1.270	-	2.513	15.11
L3	3.108	3.058	2.757	-	1.608	11.29
L4	1.144	1.122	1.02	-	1.923	10.83

In this study, the impressions of cost minimization can also be accomplished by the reduction in power loss as well as bus voltage profile improvement. The uncompensated voltage profile is shown in Figure 8 while the improvement of voltage profile after capacitor installation for all four load cases is illustrated in Figure 9. Comparing the voltage features of the system with and without the capacitor, it can be said that, the optimal allocation of capacitor regulates the voltage profile within allowable voltage regulation limits (as in Figure 8, the bus voltages are out of limitation with 0.844 p.u @ bus 2 in level 1, however, as in Figure 9, all profiles are within the allowable limits). Predominantly, the proposed method regulates the minimum bus voltage of each feeder achieving improvement above 0.911 p.u after capacitor placement (it will be described in Table 4).

Table 4. Performance analysis on optimal capacitor placement

Description	Without capacitor	With capacitor	Feeder	Voltage profile of each feeder			
				Without capacitor		With capacitor	
				Min@bus	Max@bus	Min@bus	Max@bus
Total P demand (MW)	12.11	12.11	F5	0.876@ 34	0.995 @ 2	0.913@ 34	0.997@ 2
Total Q demand (MVAr)	4.25	4.25	F6	0.878 @ 65	0.989@ 35	0.911 @65	0.992@ 35
Optimal location @ bus	-	94	F7	0.879@ 96	0.986@66	0.920 @ 96	0.990@66
Optimal capacity (MVAr)	-	0.5640	F8	0.878@115	0.989@97	0.927@115	0.992@ 97
Energy cost ($)	27480	22768.85	System voltage	0.876 @ 34	1.000 @ 1	0.911@65	1.000@1
Net saving ($)	-	4711.15					
% saving	-	17.14					

Table 4 summarizes the technical benefits and energy savings per year. The table describes how the proposed method has achieved optimal results with remarkable savings. The results of the proposed method yield a significant reduction in power loss and the cost of energy losses. The result accuracy value of the proposed approach states about 17.14% of energy cost saving with optimal capacitor injection. Therefore, the current work proves well effectiveness on OCP.

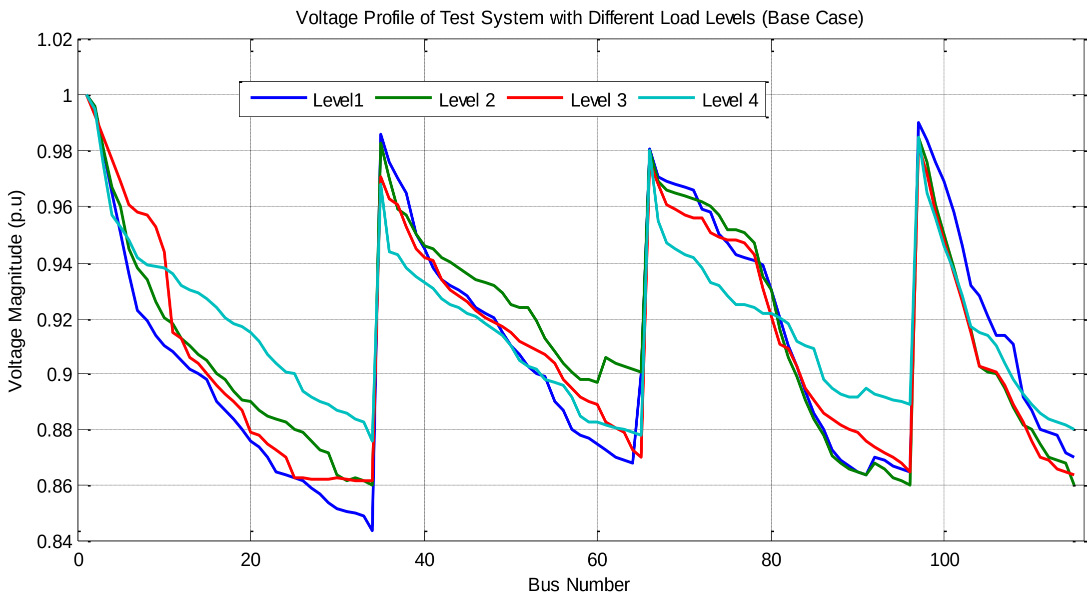

Figure 8. Voltage profile for different load levels (before capacitor placement)

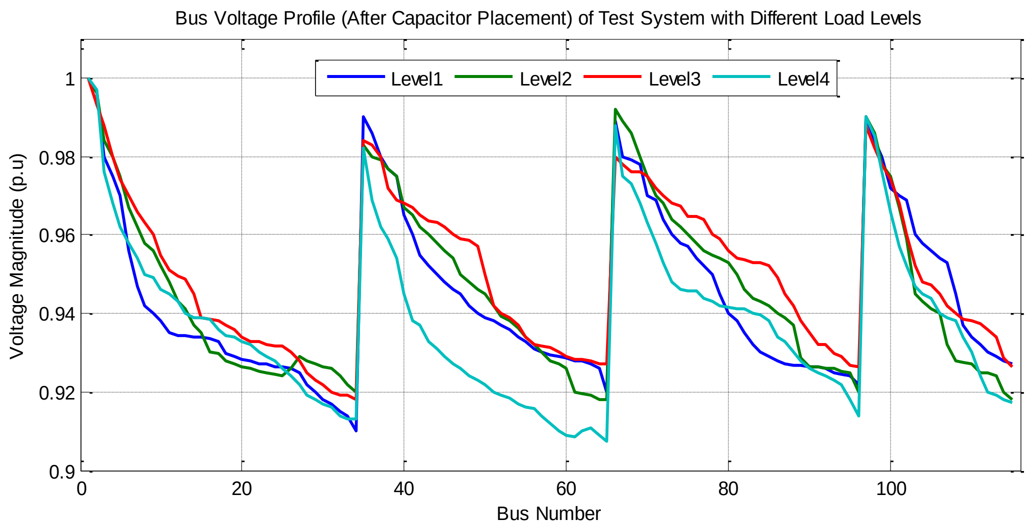

Figure 9. Voltage profile improvement for different load levels (after capacitor placement)

5.4. Comparative results with PSO and LSF

The LSF [1], [13] is used to find the candidate bus in the practical test network based on the initial load flow results. The norm of (V_i/0.095) [13] is accepted to pick the candidate buses having normalized voltage magnitudes (<1.01). After that, these candidates are tested with the initial capacitor sizing of section 5.1.

The candidate buses obtained by LSF are not enough to be satisfied with the optimal location of the capacitor. And, it is necessary to contemplate at which bus should be installed by comparing the total power losses. According to the tested results, among the nominees, the optimal site is at bus 34 with 0.3908 MVAr size, which gives the least power loss of 1.475 MW comparing the base case of 1.496 MW. The best allocation of bus 34 with the optimal size is tested with four different load levels to compare with the proposed PSO technique. The comparative results of the PSO algorithm-based OCP and LSF are tabulated in Table 5.

According to the results, even though there are different locations supported by different approaches, the results obtained by PSO is more operative than that of LSF. It can be noted that meta-heuristic optimization-based OCP considering more than one load level (segment) in daily load curve yields a reasonable solution and the practical network has resulted in more loss reduction as well as better voltage profile improvement.

Table 5. Effect of los reduction to capacitor placement

Items	Base case	Compensated	
		LSF [1], [13]	PSO
Optimal location	-	34	94
Optimal capacity (MVAr)	-	0.3908	0.564
Cost of energy loss ($)	27480	24615.76	22768.85
Net saving ($)	-	2864.24	4711.25
% Saving	-	10.42	17.14

6. CONCLUSION

In this study, the optimization method for optimal positioning and rating of the shunt capacitor in the practical distribution network was presented. Incorporating with MATPOWER toolbox, the PSO algorithm is employed to adjust the controlled variables to minimize the cost of energy losses through optimal capacitor allocation. The proposed technique successfully achieved in finding optimal size and site of the capacitor seeking the most effective candidate bus to install in which the technical and commercial benefits are attained. It is found that the proposed technique identified the optimal allocation of the capacitor that provides a noteworthy power loss reduction and voltage profile improvement of the system.

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