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Original Research Article

Optimization of Reactive Power Injection on Radial Distribution Network for Improved System Performance

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ABSTRACT

Distribution systems occupied a core position in the hierarchical structure of conventional power systems. However, several factors limit the expected efficiency of many practical distribution systems. It is, therefore, a thing of concern to power distribution engineers to seek better ways to manage both the amount of real power loss and deviation on bus voltage profile. On this premise, this paper presents the use of a shunt capacitor as a mitigating device. The initial state of the test case system was determined using the backward forward sweep (BFS) power flow technique. Cuckoo search algorithm (CSA) and voltage stability index (VSI) were employed to site and size the amount of reactive power injection. The proposed approach was tested on IEEE 33 bus system. Simulation results obtained were validated with other optimization algorithms. Results comparison showed that the proposed method outperformed binary particle swarm optimization (BPSO), real coded genetic algorithm (RCGA) and simulated annealing (SA). In a similar vein, system stability also improved as shown in the values obtained for VSI after integrating the shunt capacitor. This approach is therefore capable of strengthening the performance of the radial distribution system.

1. INTRODUCTION

The end-users of electricity obtain their day-to-day energy demand via the distribution systems. Distribution systems, therefore, form a unique part of modern power systems even with the advent of the dispersed generation, which is a smart means of boycotting transmission systems. Operationally, the distribution systems' voltage level is comparatively lower compared to the transmitted voltage and degree of incessant short circuit faults at this arm of power system is significantly higher (Prakash and Lakshminarayana, 2017). Furthermore, many of the customer's connected loads are more of inductive loads which are responsible for the high power losses manifesting in form line losses and substantial violation in bus voltage, particularly for buses at the far end of the primary distribution substation (Oliveira *et al.,* 2010; Pradeepa *et al.,* 2015). The real and reactive power losses account for the aggregate power losses in the distribution feeder. The primary cause of real power loss is traceable to the flow of active component of current required by the consumers' connected loads. This has devastating effects on power transfer efficiency and bus voltage deterioration (Park *et al.,* 2009; Naik *et al.,* 2013). With the recent exponential growth in consumer loads on 11 kV feeders' radial distribution systems, there is, therefore, a need for a constant check on the reactive power balance, if these loads surge will be safely accommodated without resulting into severe power loss and voltage violation from the approved statutory standard (Murty and Kumar, 2013; Olabode *et al.,* 2020).

The use of shunt capacitor has been reported in several pieces of literature not only as a viable means of reducing the real power loss but also as a good alternative for sustaining the system voltage profile within the permissible statutory limits aside from power factor correction and system stability enhancement (Sajjadi *et al.,* 2013; Esmaeilian *et al.,* 2014; Abdelaziz *et al.,* 2016; Ali *et al.,* 2016). Tap-changing transformers, network feeder reconfiguration, shunt capacitor, distributed generation, and distribution flexible alternating current devices distribution static synchronous compensator (D-STATCOM) are viable ways of mitigating challenges on the radial network (Sedighizadeh *et al.,* 2014; Muthukumar and Jayalalitha, 2016; Sarkar *et al.,* 2020). To be able to fully optimize the benefits that can be derived due to integration of these aforementioned devices, there is need to see to the number of optimal sizes and the most appropriate locations where these devices are to be placed within the network, otherwise, the system stands to be adversely affected (Kalyuzhny *et al.,* 2000*)*.

A critical survey of literature on optimum allocation and sizing of shunt capacitors as local reactive power compensation on radial distribution networks showed that four solution methodologies can be adopted; analytical approach (Bae, 1978), numerical programming approach (Baldick and Wu, 1990), heuristic techniques (Chis *et al.,* 1997) and artificial intelligence approaches (Sundhararajan and Pahwa, 1994). A detailed comprehensive comparison of these approaches was presented by Sundhararajan and Pahwa, (1994) and based on the comparison made, it can be deduced that artificial intelligence techniques are promising alternative means of siting and sizing of a shunt capacitor. Prominent artificial intelligence that has been employed in sizing and locating shunt capacitors in radial distribution system (RDS) is thus surveyed.

The cost, minimization of power loss as well as enhancement of bus voltage was implemented using whale optimization algorithm (WOA) on IEEE 34 and 85 bus (Prakash and Lakshminarayana, 2017). The results obtained was compared to particle swarm optimization (PSO), mixed-integer linear programming (MILP), plant growth stimulation (PGS), and backtracking search optimization algorithm (BSOA) using cost minimization, total power loss and bus voltage magnitude improvement as performance metrics. Furthermore, Kalyuzhny *et al.* (2000) employed a genetic algorithm (GA) for optimal siting and sizing of shunt capacitor for reactive power injection on the radial feeder, the injected reactive power improved the system voltage profile and minimized the system real power loss significantly. Injeti *et al.* (2015) used Bat algorithm (BA) and cuckoo search algorithm (CSA) to place shunt capacitors of different sizes on IEEE 34 and 85 bus with the sole aim of minimizing real power loss and improving the system voltage magnitude. The results obtained were compared with particle swarm optimization (PSO), evolutionary algorithm (EA), GA, ant bee colony (ABC) and harmony search (HS), and in all BA was found to be superior in term of performance.

Reduction of power losses on radial distribution networks has been attempted with diverse approaches by Nigerian authors. For instance, Prakash and Lakshminarayana, (2017) employed CSA to determine the optimal site where shunt capacitors are to be placed on IEEE 33 and on a Nigerian 11-kV feeder (Ayepe 34-bus). The cost minimization, loss reduction, and voltage profile were captured as the multi-objective function, different optimal locations and sizes were investigated.

The result obtained using CSA was better than PSO, IMDE, GSA, and WCA, and in all, CSA performed credibly than them all. Also, Olabode *et al.* (2019a) employed CSA and loss sensitivity factor (LSF) employed as a two-stage approach to optimal site and size of shunt capacitors on IEEE 15 and Yale 17 bus 11-kV feeder in Nigeria. The real power loss minimization and voltage profile enhancement form the aim of their research, and the results obtained was benchmarked with DE, PSO, flower pollination algorithm (FPA) and analytical method. In all, CSA achieved an optimal reduction in losses and better improvement in voltage magnitude (Olabode *et al.,* 2019a).

In similar vein, Firefly algorithm (FA) and voltage stability index was proposed to optimally site and size shunt capacitors on Ayepe 34-bus 11-kV feeder in Nigeria. Reduction in real power loss with the proposed approach was reported to be significant in addition to enhancing voltage magnitude and system voltage stability index (Olabode *et al.,* 2019b). Okelola, (2018) employed an analytical approach to mitigate real power loss on several kinds of 11-kV feeders within Osogbo town in Nigeria. The approach employed was found to be computationally complex and more so, it was based on guesswork. An analytical approach was used to site and size shunt capacitor with an intention to mitigate harmonic distortion and power factor correction (Oodo *et al.,* 2013). A heuristic technique was used to address loss minimization, power factor correction, and cost of shunt capacitors.

Based on the literature reviewed, it was clearly observed that there are different applications on the use of artificial intelligence for solving distribution network problems, and to further extend the effort of earlier researchers, this present work seeks to implement the recommendation suggested in work carried out by Olabode *et al.* (2019a).

2. MATERIALS AND METHODS

2.1. Description of IEEE 33 Radial Distribution Feeder

This test system among others are specifically designed for verifying different techniques that could enhance the performance of real life distribution network. It has thirty-three buses, thirty-two branches with a base voltage, base MVA and load demand of 12.66 kV, 100 MVA respectively as shown in Figure 1.

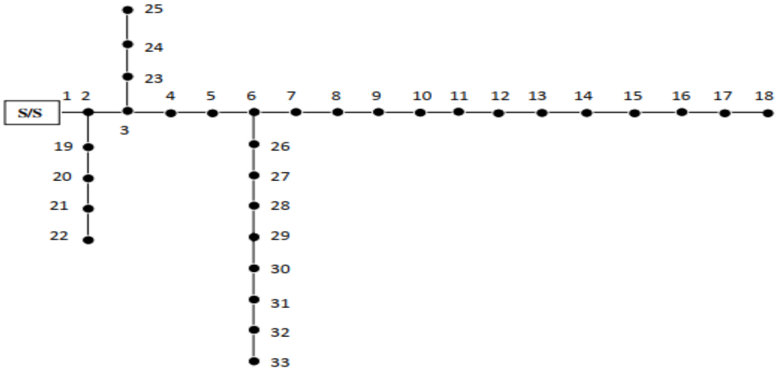

Figure 1: One-line diagram of IEEE 33-bus RDS

2.2. Implementation Software

The data required for this research include the line data (line resistance and reactance) and bus data (real and reactive power loading). The data preparation was done using Microsoft Excel while the proposed approach was implemented in MATLAB environment.

2.3. Mathematical Modeling of the Formulated Problem

2.3.1. Load flow solution methodology

Backward forward sweep is a two-stage technique in which each node voltage is calculated during the forward sweep. Usually, the computation starts from the source node of the feeder to last node while the current and power flow in each branch is computed during the backward sweep in reverse order. The detailed mathematical equations for the computation of node voltage, current and real and reactive power for this technique has been comprehensively reported (Olabode *et al.,* 2019a; Olabode *et al.,* 2019b; Anayo, 2009; Mobini and Roohi, 2009).

2.3.2. Voltage stability index

One of the viable tools to predict potential sites for placement of shunt capacitors within the 11-kV feeder is the voltage stability index. It is usually derived via the base case power flow analysis. There is a need to arrange the value obtained in ascending order; as this helps to determine the order of sequence for reactive power compensation. Node carrying the minimum value of VSI is referred to as the most sensitive node to voltage collapse (Devabalaji *et al.,* 2019). The value for the VSI was obtained using Equation (1) given by Devabalaji *et al.,* (2019).

$$VSI_{(m+1)} = |V_m|^4 - 4\left[P_{m+1,eff} \times X_m - Q_{m+1\,eff} \times R_m\right]^2 - 4\left[P_{m+1,eff} \times R_m + Q_{m+1} \times X_m\right]|V_m|^2 \quad (1)$$

where V_m= bus voltage magnitude at mth bus, X_m = line section reactance between m and $m+1$, R_m = line section resistance between m and $m+1$, $Q_{m+1\,eff}$ =total effective reactance power load through the bus $m+1$ and $P_{m+1,eff}$ = total effective real power load fed through the bus $m+1$

2.4. Cuckoo Search Algorithm

CSA came to being in 2009 by Yang and Deb (Yang and Deb, 2009) and was based on the parasitic reproductive brooding style of a bird called Cuckoo. Figure 2 shows the Cuckoo with its parasitic egg. The unique strategy employed by the Cuckoo in the surrogate nest to survive when hatched by the host bird is as illustrated in Figure 3. This strategy improved the Cuckoo's ability to dominate and prevent the original surrogate bird's egg from surviving as it hatches earlier and stylishly pushes other eggs out of the nest.

Figure 2: Cuckoo and its parasitic egg in host nest (Panday, 2010)

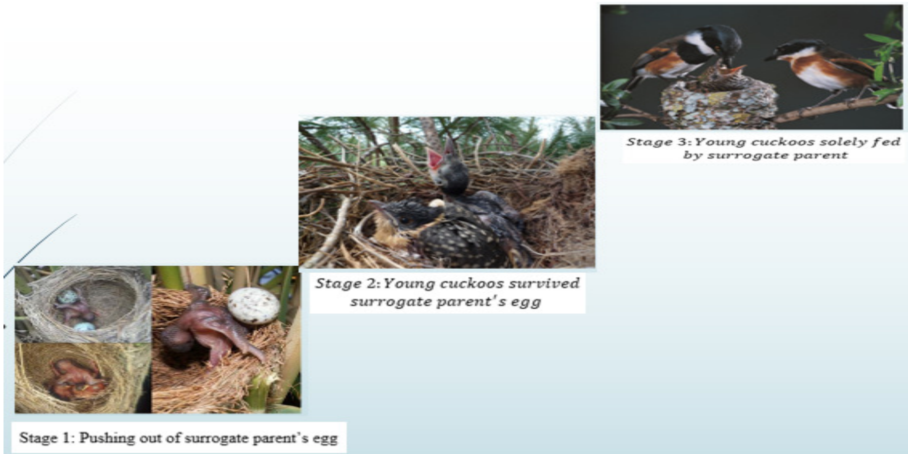

Figure 3: Cuckoo's strategy for survival in host nest (Panday, 2010)

Several authors such as Panday, (2010), Ajenikoko and Olabode (2017), Yang and Deb, (2014), Dejam *et al.* (2012), and Chandrasekaran and Simon, (2012) have given a detailed explanation of this algorithm. The nest where the Cuckoo lays its egg is usually randomly chosen and was modeled using Equation (2) given by Kumar *et al.* (2014).

$$M_{pq}^{gen+1} = M_{pq}^{gen} + \left(X_{pq} * Levy(\lambda) \times \alpha\right) \tag{2}$$

λ= constant value, $\alpha =$ randomly generated number usually lies between -1 and 1, p and q represents indexes randomly chosen.

Also, the probability with which the surrogate bird identifies Cuckoo egg was modeled by Equation (3) as given by Devabalaji *et al.* (2016).

$$Pa_{(q)} = \left(\frac{0.9 * fit_{(q)}}{max(fit)}\right) + 0.1 \tag{3}$$

where $fit_{(q)}$ stands for the solution fitness function, $max(fit)$ stands for the maximum value of fitness function. The possibility of a surrogate bird discarding the cuckoo egg when discovered and constructing a new nest was modeled using Equation (4) given by Devabalaji *et al.* (2016).

$$Nest_{(q)} = M_{q,min} + rand\ (0,1) * \left(M_{q,max} - M_{q,min}\right) \tag{4}$$

Where $M_{q.min}$ is the old nest and $M_{q.max}$ is the new nest

2.5. Step by Step Implementation Approach

There are two stages involve in the implementation of this proposed approach. For the first stage, VSI determines potential sites where capacitors can be placed. The essence of this step is to reduce the algorithm exploration and exploitation of search space. For the second stage, CSA determines the suitable sites among the pre-selected sites and also the optimal sizes of shunt capacitors required for compensation. BFS has been reported severally to be the most suitable for RDS load flow analysis forms the backbone of this work. Mobini and Roohi,(2009) presented details of BFS. The procedural steps to achieve the set objectives are as listed thus:

> Step I: The load flow study was conducted using BFS equations given by Mobini and Roohi,(2009) to get the initial power losses, system voltage magnitude and the angle at each buses.

Step II: The VSI was computed using Equation (1) from the base case power flow to fish out possible potential sites suitable for location of shunt capacitor.
Step III: The inequality constraints for bus voltage magnitude, capacitor sizes were imposed to generate randomly the initial population of (n) host nests
Step IV: Use Equation (2) to obtain new cuckoo population called $F_{(a)}$
Step V: Employ Equation (3) to evaluate the fitness function of step (IV)
Step VI: Generate a new nest from step V called $F_{(b)}$
Step VII: If $F_{(a)}$ is greater than $F_{(b)}$ go to step (VIII), if this does not hold go to Step (IX)
Step VIII: Replace $F_{(b)}$ with the new solution
Step IX: Generate new nest in new location with the aid of Equation (2)
Step X: Pick the best current nests
Step XI: Check the stop criteria has been fulfilled, if reached go to step (XII), else go to step (IV)
Step XII: Print the optimal sites and optimal sizes of shunt capacitors

3. RESULTS AND DISCUSSION

3.1 Results of Load Flow Analysis

The branch real power loss obtained from BFS load flow conducted is as shown in Table 1. Observation of Table 1 showed that a significant real power loss of about 52.08 kW occurred in branch two (2) being a link between bus one (1) and bus two (2). By inference, this accounts for 24.68% of the total network real power loss. Also, a typical trend- buses far from the distribution substation tends to experience poor voltage profile while those closer to the substation are always within the approved window- expected of a real radial distribution network was noticed which justifies the reason for consumers at the far end of the radial feeder usually experiencing low voltage since a large part of the voltage from the substation would have dropped significantly before reaching them. Furthermore, branch thirty-two (32), which connects bus thirty-two (32) to bus thirty-three (33) experienced the least real power loss which amounts to about 0.0065% of the total network real power loss. Aggregating all the losses in all the branches gives 210.99 kW as the total network real power loss.

Table 2 depicts the initial voltage magnitude and angles before reinforcement using the BFS load flow techniques. The minimum bus voltage magnitude occurred at bus eighteen (18) and was estimated to be 0.90377 p.u. If a tolerance of $\pm 5\%$ was assumed, bus one (1) to bus seven (7), and bus nineteen (19) to twenty-six (26) have their voltage magnitude within $0.95 \leq |V| \leq 1.05\, p.u.$ It could be inferred that these buses are not susceptible to voltage collapse; hence injection or absorption of reactive power might not be necessary at this point.

However, buses eight (8) to eighteen (18) and twenty-seven (27) to thirty-three (33) revealed a voltage magnitude below the minimum approved limits of 0.95 p.u. Such buses can be regarded as defective and are points of concern for the kick-starting of voltage collapse. Technically, these buses are potential sites for injecting reactive power to compensate for reactive power inadequacies. For adequate reactive power compensation, the voltage stability of each of the buses was investigated with a metric called voltage stability index. The VSI can predict the order of buses to be compensating purposefully to raise the entire system voltage, consequently translating to an appreciable reduction in system real power losses. The results obtained for the voltage stability index of each bus were as shown in Table 3. The branch that links bus seventeen (17) and eighteen (18) was observed to have the least value of VSI and was evaluated to be 0.66889 p.u. A critical evaluation of the results obtained for VSI showed that the order of trials to locate optimal sites are as follows 17, 16, 15, 13, and 32. Intuitively, buses seventeen and eighteen are the most critical buses being highly susceptible to voltage collapse. Furthermore, a smaller value for VSI was also observed for branches thirteen (13), fourteen (14), fifteen (15), sixteen (16), and thirty-two (32). Consequently, these buses were treated as preselected sites in the optimization stage and thus became a search space for the CSA to explore and exploit while trying to find the optimal site(s) for siting shunt capacitor.

Table 1: IEEE 33 branch real power loss

Branch no.	Real power loss before shunt capacitor placement (kW)
1	12.30
2	52.08
3	20.05
4	18.85
5	38.57
6	1.95
7	11.87
8	4.27
9	3.62
10	0.57
11	0.89
12	2.72
13	0.74
14	0.36
15	0.29
16	0.26
17	0.05
18	0.16
19	0.83
20	0.10
21	0.04
22	3.18
23	5.14
24	1.29
25	2.60
26	3.33
27	11.31
28	7.84
29	3.89
30	1.59
31	0.21
32	0.01
Base case total network loss	210.99

Table 2: Bus voltage magnitude and angle

Branch no.	Initial voltage profile (p.u)	Initial voltage angle (Rad)
1	1.00	0.00
2	1.00	0.01
3	0.98	0.09
4	0.98	0.16
5	0.97	0.23
6	0.95	0.13
7	0.95	-0.09
8	0.93	-0.25
9	0.92	-0.32
10	0.92	-0.38
11	0.92	-0.38
12	0.92	-0.37
13	0.91	-0.46
14	0.91	-0.54
15	0.90	-0.58
16	0.90	-0.61
17	0.90	-0.68
18	0.90	-0.69
19	0.99	0.01
20	0.99	-0.06
21	0.99	-0.08
22	0.99	-0.08
23	0.98	-0.08
24	0.97	-0.10
25	0.97	0.06
26	0.95	-0.02
27	0.94	-0.06
28	0.93	0.17
29	0.93	0.23
30	0.92	0.31
31	0.92	0.39
32	0.92	0.41
33	0.92	0.39

Table 3: Base case VSI on IEEE 33 test system

Branch no.	Base case VSI
1	1.00
2	0.99
3	0.93
4	0.91
5	0.88
6	0.81
7	0.80
8	0.75
9	0.73
10	0.72
11	0.71
12	0.71
13	0.69
14	0.68
15	0.68
16	0.67
17	0.66
18	0.98
19	0.99
20	0.97
21	0.97
22	0.93
23	0.92
24	0.89
25	0.81
26	0.81
27	0.79
28	0.76
29	0.74
30	0.72
31	0.71
32	0.70

3.2. CSA Optimization Results on IEEE- 33 Bus

The essential parameters of CSA were updated into the MATLAB source code developed for optimal location and sizing of reactive power compensator used on this test system. After several trials, the optimal value for these control parameters were as presented in Table 4 and with these optimal values, a significant improvement was recorded in term of voltage magnitude and system voltage stability index, which consequently translated to a colossal reduction in the entire system real power losses when compared with what was obtained before reinforcement. The convergence plot obtained for the fitness function of the objective function with these optimal values was as shown in Figure 4. It was observed that it converged in less than fifteen generation (iterations), yielding buses fifteen (15), seventeen (17), and thirty-two (32) as the optimal sites among the preselected sites. The optimal size of shunt capacitor placed at these buses are 750, 100, and 150 kVar respectively. With these optimal sites and the optimal sizes of the compensator injected, a total real power loss of 151.53 kW was recorded. When this value was compared with the base case scenario, about 28.18% reduction in real power loss was achieved. Looking at the effect of this compensation at each branch of the network, it was observed that a significant reduction occurred at each branch of the network as seen in Table 5. At branch two (2), about 23.36% reduction was obtained as the power loss reduced significantly from 52.08 kW to 39.91 kW which translated to 23.36 % reduction. Similarly, the branch with the least power loss even at the base case scenario also witnessed an appreciable reduction of about 5.24 % as it reduced from 0.01317 to 0.01248 kW.

Table 4: CSA control parameter optimal values

Parameter of CSA	Optimal values
No of host nest	50.0
Pa	0.25
Step size	1.5
Iteration maximum	100.0
Levy coefficient	0.5

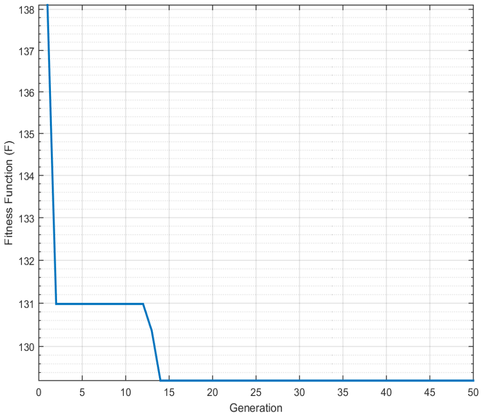

Figure 4: Objective function fitness curve

Also, presented in Figure 5 is the comparison between the system voltage profile prior and after injection of reactive power, the system voltage profile was observed to be appreciably enhanced after inclusion of the compensating device. Also, bus eighteen being the bus with the least voltage magnitude was found to improve from 0.90 to 0.91 p.u which amounts to about 1.13% improvement. Furthermore, a noticeable improvement in voltage magnitude was also observed in buses three to sixteen and twenty-two to thirty-three. Figure 6 shows the comparison of system VSI prior and after injection of reactive power; it was observed that minimum VSI improved from 0.67 to 0.70 p.u, while others also improved remarkably. The overall effect of the injected power is as summarized in Table 6.

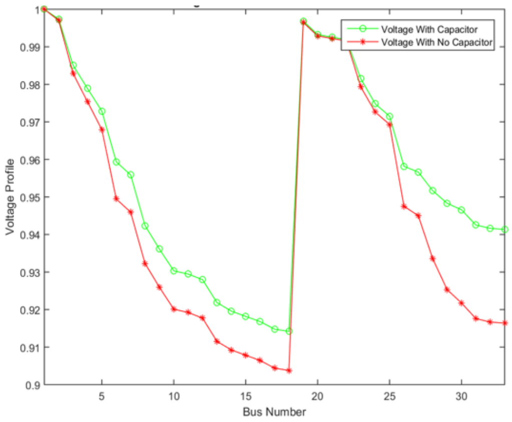

Figure 5: System voltage profile before and after compensation

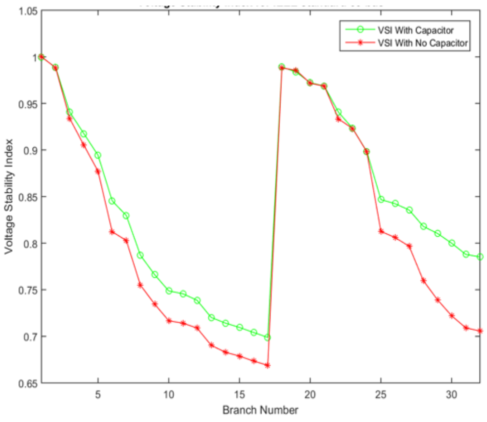

Figure 6: Comparison of system voltage stability index

Table 5: Effect of shunt capacitor placement on branch real power loss on IEEE 33 bus feeder

Branch no.	Branch real power loss before shunt capacitor placement (kW)	Branch real power loss after shunt capacitor placement (kW)
1	12.30	9.73
2	52.08	39.91
3	20.05	13.75
4	18.85	12.73
5	38.57	25.79
6	1.95	1.90
7	11.87	11.61
8	4.27	4.17
9	3.62	3.54
10	0.57	0.55
11	0.89	0.88
12	2.72	2.66
13	0.74	0.73
14	0.36	0.36
15	0.29	0.28
16	0.27	0.25
17	0.05	0.05
18	0.16	0.16
19	0.83	0.83
20	0.10	0.10
21	0.04	0.04
22	3.18	3.17
23	5.14	5.12
24	1.29	1.28
25	2.60	1.20
26	3.33	1.48
27	11.30	3.83
28	7.84	2.18
29	3.89	1.51
30	1.59	1.51
31	0.21	0.20
32	0.01	0.01
Total real power loss	210.98	151.53

Table 6: Summary of overall effect of shunt capacitor on IEEE 33 bus RDS

Metrics of evaluation	Devoid of reactive power compensation	With reactive power compensation
System minimum voltage (p.u)	(bus 18) 0.90378	(bus 18) 0.91418
System minimization VSI	(bus 17) 0.66889	(bus 17) 0.69889
Total power loss (kW)	210.98	151.53
Buses and capacitor Sizes (kVar)	-	[bus 15, 750 kVar); (bus 17, 100 kVAr); (bus 32, 150 kVar]
Total injected reactive power (kVar)	-	1000 kVar

3.3. Results Validation

The effectiveness of the approach implemented was validated with some selected optimization algorithms found in published articles which include binary particle swarm optimization (BPSO) (Kumar *et al.,* 2014), real coded genetic algorithm (RCGA) (Baghipour and Hosseini, 2014) and simulated annealing (Chiang *et al.,* 2010). The observations showed that a lesser amount of reactive power was injected via shunt capacitor with the proposed approach when compared with that injected using SA and BPSO. Even though the amount of injected power with the use RCGA was lesser, yet loss reduction achieved using CSA was much better than that of RCGA. In all the magnitude of reduction in real power with the proposed approach was better than the other optimization algorithms investigated and a summary of the performance comparison is presented in Table 7.

Table 7: Results validation

Optimization algorithms	Optimal site (kVar) and sizes of shunt capacitor	Amount of reactive power injected (kVar)	Total real power loss (kW)	% Loss reduction
Base case	-	---	210.9876	---
BPSO	Bus 2 (305.6 kVar), Bus 5 (952.5 kVar), Bus 30 (127.9 kVar)	1386.00	176.47	16.36
RCGA	Bus 7 (100 kVar), Bus 12(100 kVar), Bus 28 (100 kVar), Bus 29 (100 kVar) Bus 30 (100 kVar)	500.00	172.56	18.21
SA	Bus 10 (450 kVar), Bus 14 (900 kVar), Bus 30 (350 kVar)	1700.00	151.75	28.07
CSA with VSI approach	Bus 15 (750 kVar), Bus 17 (100 kVar), Bus 32 (150 kVar)	1000.00	151.53	28.18

4. CONCLUSION

The performance of the radial distribution network can be enhanced by adequate injection of reactive power in the system. This paper has thus applied CSA and VSI to locate and size shunt capacitors on IEEE 33 –bus distribution network to minimize real power loss and enhance bus voltage magnitude. The number of locations previously pre-determined with VSI was drastically reduced to three. This algorithm's optimal sites and sizes achieved a substantial reduction in total real power loss. In addition, voltage magnitude improved significantly. Similarly, system stability was observed to appreciate based on the values obtained for the system voltage stability index. It is concluded that VSI is capable of predicting suitable sites where shunt capacitors are to be integrated. At the same time, CSA demonstrated good searching ability in locating the optimal sites and optimal sizes of shunt capacitors required for adequate compensation. A new direction for further research can employ the index vector method, loss sensitivity factor and power loss index with CSA to site and size shunt capacitor using the same radial distribution system.

5. CONFLICT OF INTEREST

There is no conflict of interest associated with this work.

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