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Optimal Placement of Charging Station and Capacitor in Electrical Radial Distribution Network

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Abstract

One of the major contributor of global warming and environmental changes which is considered as global problem is fossil operated internal combustion engines vehicles. To sort out this problem, enhanced battery technology and subsidies provided by the Government has caused rapid increase in number of electric vehicles (EVs) which requires charging station (CS) connected to the existing electrical distribution network. Random placement and sizing of such increasing number of CS causes adverse impact on the network like increase in power loss, voltage instability of the system, high voltage deviation at various buses, etc. This paper proposes a methodology for optimal placement and sizing of CSs and allocates capacitor optimally by using particle swarm optimization algorithm in the distribution network to improve the system parameters. Simulation is carried out on the IEEE-34 bus radial distribution network. The objective function to be optimized considers the parameters like power loss, voltage stability index, voltage sensitivity factor, cost of capacitor, cost of charging station. Results shows the best allocation of CSs and advantages of capacitor placement.

Keywords

Electric Vehicles(EVs), Charging Station Placement, Capacitor placement, Particle Swarm Optimization (PSO) Algorithm, Voltage Sensitivity factor (VSF), Voltage Stability Index (VSI).

1. Introduction

Globally, the demand of energy is increasing day by day but the finite nature of fossil fuels along with increasing problem created by global warming and climate change are the main concerns of 21st century. It is well known that one of the significant contributors of climate change is fossil fuel operated vehicles. Researchers have found that replacement of fossil operated internal combustion engine vehicles by battery operated electric vehicles (EVs) have significant impact on reduction in greenhouse gas emission thus minimizing the global warming problem [1]. Electric mobility is expanding at a rapid pace and it is estimated to have global deployment of 23 million electric vehicles (excluding two/three wheeler) by 2030. In 2018, the global electric car fleet exceeded 5.1 million, up by 2 million from the previous year and almost doubling the number of new electric car sales. The People's Republic of China remains the world's largest electric car market, followed by Europe and the United States. Norway is the global leader in terms of electric car market share [2].

Charging station (CS) is basically an element in an infrastructure that supplies electric energy for recharging of plug-in EVs and hybrids from an electric source to EV outlets through communication equipment for a safe flow[3].Charging infrastructure for EV is composed of two main areas: charging facilities and charging devices. Charging facilities are categorized as home charging and public charging where public charging is further categorized as opportunity CS, fast CS and battery swapping CS. Among various charging devices the conductive charger for EVs are most widely used till to the date because such type of charger has the advantage of maturity, simplicity and low cost due to simple making the use of plugs and socket to conduct electrical energy via physical contacts [4]. Due to improvement on battery technology used in EV, CS technology and subsidies provided by the Government bodies, the integration of CS in the existing distribution network is increasing day by day.

Inappropriate siting and sizing of EV charging stations could have negative impact on the development of EVs, layout of the city traffic network, convenience of EV's drivers and electric parameters of the network among which voltage profile and power loss are the two main factors to be considered [5]. Study on the effect of different CS rates (low, medium, and high) and various charging periods on power loss, voltage profile, load profile, and peak demand shows that varied charging rates and charging periods have different impacts. High voltage lines are most affected by high power and quick CS. Charging vehicles with CS placed in low voltage lines may cause transformer overloading. Impact of EV charging station load on the voltage stability, power losses, reliability indices, as well as economical losses of the distribution system can withstand placement of fast charging stations at the strongest buses up to a certain level, but the placement of fast charging stations at the weak buses of the system hampers smooth operation of the power system [1].
In this wok an objective function is developed for best optimal sitting and sizing of CSs in the existing radial distribution network considering the zonal placement by using particle swarm optimization (PSO) algorithm. Various research have shown the benefit of optimal placement of capacitor in distribution network which is utilized in this work to address the adverse technical impact such as voltage stability, power loss and voltage profile degradation caused by optimal integration of CSs.

2. Mathematical Model

2.1 Load Flow

The conventional power system load flow algorithm are slow and have convergence issue when implemented in distribution network due their special characteristics such as radial or weak structure, multi-phase and unbalance operation, unbalanced load, large number of branches and nodes, high R/X values, etc. Hence, in this work an efficient backward and forward sweep method is used considering power as flow variable. The method is described as follows :-

a) Backward Sweep :- In this sweep the effective active and reactive load at each bus is calculated including branch losses starting from end bus and moving towards to root node (substation bus).

b) Forward Sweep :- In this sweep starting from root node and moving towards end bus, voltage is calculated by $|V(m2)| = \sqrt{|B(j) - A(j)|}$

Where,
$A(j) = P(m2)R(j) + Q(m2)X(j) - 0.5|V(m1)|^2$
$B(j) = \sqrt{A(j) - [R^2(j) + X^2(j)][P^2(m2) + Q^2(m2)]}$
In the above equation, m1 and m2 are sending and receiving end nodes respectively of branch j, P(m2) and Q(m2) are effective active and reactive load respectively of the node m2 calculated in backward sweep and, R(j) and X(j) are resistance and reactance respectively of branch j. Branch j active (LP(j)) and reactive (LQ(j)) power losses can be obtained respectively by :-

$$LP(j) = \frac{R(j) * [P^2(m2) + Q^2(m2)]}{|V(m2)|^2}, \text{ and}$$

$$LQ(j) = \frac{X(j) * [P^2(m2) + Q^2(m2)]}{|V(m2)|^2}$$

Power losses of a distribution network refer to typical I^2R losses of the line and the total power loss of the system having branches n is given by $P_{loss} = \sum_{j=1}^{n} LP(j)$

2.2 Charging Station Placement

There are different significant factors such as various electrical parameters of the system, transportation system, economic cost, user convenience,etc which influence the optimal planning of charging station in the existing distribution network. The driving range is not now major issues due to availability of fast/rapid charging station and availability of EVs in the market having the driving range more than 200 mile. In this work total active power loss, voltage stability and economic costs are considered for optimal placement of CSs without any violation of various electrical constraints.
Voltage stability is the ability of the power system to maintain the steady acceptable voltage at all the buses under normal operating conditions and when an external disturbance is applied. A voltage stability criterion used in many stability studies is that voltage of all the system buses must be within acceptable limits. Voltage stability is indeed a local phenomenon but, in some cases, it may lead to severe voltage collapse. In this work Voltage Sensitivity Factor (VSF) and Voltage Stability Index (VSI) are used for voltage stability analysis. VSF is defined mathematically as the ratio of change in voltage

magnitude (dV) to change in active load (dP)and is given by

$$VSF = \left|\frac{dV}{dP}\right|, \forall P < P_{max}$$

is used for selection of candidate bus for CSs placement. The bus which has least value of VSF is considered as strongest and highly stable bus of the system. Similarly, mathematically VSI is given by :-

$$VSI(m2) = |V(m1)|^4 - 4\{P(m2)X(j) - Q(m2)$$
$$R(j)\}^2 - 4\{P(m2)R(j) + Q(m2)X(j)\}|V(m1)|^2$$

Where, m1 and m2 are sending and receiving end nodes of branch j and P, Q, R and X are the parameters as defined in section 2.1. For stable operation of the radial distribution networks $VSI(m2) \geq 0, \forall$ nodes. The node at which the value of the stability index is minimum, is more sensitive to the voltage collapse [6].

The objective function to be minimized for optimal placement and sizing of charging station is defined by $OF = W_3VP + W_4CI$, where, $VP = W_1A + W_2B$,

$$A = \frac{VSI_{base}}{VSI},\ B = \frac{P_{loss}}{P^{base}_{loss}} \text{ and, } CI = \frac{CS^{inv} + K_p * P_{loss}}{K_p * P^{base}_{loss}}$$

Here, K_p is the equivalent cost per unit of power loss (\$/kW), P_{loss} is total power loss of the system in kW, CS^{inv} is the investment cost of charging station, and W_1, W_2, W_3 & W_4 are the weighting factors.

The constraints considered for charging station placement objective functions are :-

a) CS Constraints :- The size of each charging station CS(i) should be restricted as : $CS^{min} \leq CS(i) \leq CS^{max}$ and, for selecting higher capacity of charging station total capacity of CS CS_{total} is limited as : $CS_{total} \geq CS^{min}_{total}$, where $CS^{min}(CS^{max})$ is the minimum (maximum) size of each charging station

b) Voltage Tolerance :- Voltage of each bus $V_b(i)$ should be between the minimum V_b^{min} and maximum V_b^{max} range of voltage as : $V_b^{min} \leq V_b(i) \leq V_b^{max}$

In literature, different kinds of load models for EVs CS has been found such as constant current load, constant power load, constant impedance load, and static load model (constant power and voltage dependent load). Among these the constant power and voltage dependent load model for EV fast charging station is best representation of realistic mode and is considered in this work, which is represented as [7] :

$$\frac{P}{P_0} = 0.9601 + 0.0939\left(\frac{V}{V_0}\right)^{-3.7145}$$

Where, P_0 is the power consumption at reference voltage V_0

2.3 Capacitor Placement

Different objective functions may be defined for capacitor placement. Since, the main goal of placing the compensating capacitors along the distribution feeders is to reduce the total network losses and bring the buses voltages within the allowable limits while minimizing the total cost, in this work, the objective function to be minimized for placement of capacitor is formulated as [8] :- $OF = C^{invest} + C^{loss}$. C^{loss} is the system loss cost and C^{invest} is investment cost of capacitor defined as,

$$C^{invest} = \sum_{j=1}^{n} K^c_j Q^c_j$$

Where, K^c_j is the cost of capacitor in \$/kVAR installed at j^{th} bus, Q^c_j is the total size of capacitor in kVAR installed at j^{th} bus, and n is the total number of capacitor. The following constraints should be satisfied for optimal allocation and sizing of the capacitor in the existing distribution network :-

a) Bus Voltage Tolerance :- Voltage of each bus V_i should be between minimum V_i^{min} and maximum V_i^{max} range of voltage, i.e. $V_i^{min} \leq V_i \leq V_i^{max}$

b) Size of Capacitor :- Size of each capacitor Q_c should lies between a minimum Q_c^{min} and maximum Q_c^{max} value range, i.e. $Q_c^{min} \leq Q_c \leq Q_c^{max}$.

c) Bus Capacitor :- At each bus total size of capacitor C_i should be less than a certain maximum C_i^{max}value, i.e. $C_i \leq C_i^{max}$

2.4 Algorithm

Among the various algorithm available in literature for optimizing the problem mentioned in this work, particle swarm optimization (PSO) algorithm is selected for study. PSO is a stochastic optimization technique, closely related to the two researches: one is evolutionary algorithm and other is artificial life. In PSO the particle swarm system obeys the five basic principle such as proximity (carrying simple space and time computation), Quality (sensing the quality change in environment and response it), Diverse Response (not limiting the way to get the resources in a narrow space), Stability (not changing the behavior mode with every environmental change) and Adaptability (changing the behavior mode when the change is worthy). It solves a problem by having a population of candidate solutions, here dubbed particles, and moving these particles around in the search-space according to simple mathematical formulae over the particle's position and velocity. Each particle in PSO keeps track of its coordinates in the problem space, which are associated with the best solution (fitness) it has achieved so far. This value is called P_{best}(personal best). Another "best" value that is tracked by the global version of the particle swarm optimizer is the overall best value and its location obtained so far by any particle in the population. This location is called g_{best}(global best) [9].

3. Methodology

The optimal sizing and placement of charging station in electrical distribution network along with placement of capacitor by using PSO algorithm is done in this work by the following steps :-

Step 1: At first IEEE-34 bus radial distribution system as shown in appendix figure 5 selected for study whose line and load data can be found in [10]. Based on calculation of VSF of each bus first 15 most stable buses are selected as candidate bus for placement of charging station. These 15 buses are divided into 5 zones so that CS will get distributed in different sectors of the selected system. As explained in literature fixed size of charging station are available in market, so accordingly in each zone certain size of CSs are placed for selection as shown in table 1. The selected size of charging station is combination of fast and slow chargers as explained in [11] [12].

Step 2: PSO algorithm is used to select the size and position of charging station from candidate solution from each zone as required. After placement of the CSs in the exiting distribution network load flow is run to obtain the value of objective function. As per the output of objective function PSO selects various combination of position and size until best result is obtained.

Table 1: Size of Charging Station as per zone

Zone	Size Selected in kW			
1	655	430	520	175
2	266	226	211	119
3	289	249	234	142
4	264	214	164	271
5	266	226	211	119

Step 3: In this work to select higher sizes of CSs, total capacity of CSs is limited to minimum values 900, 1200, 1400 and 1450 kW to test the suitability of selected method. For the above selected total minimum capacity limit allocation of charging station is done considering load model of CSs as described in section 2.2.

Step 4: Capacitor available in market of discrete size and price also varies as per size, so in this study the candidate size of capacitor selected is as shown in table 2 [8]. By using PSO algorithm optimal allocation of capacitor is done with all bus as candidate bus, in presence of charging station as obtained in step 3.

Table 2: Candidate size (in kVAR) and cost (in $) of Capacitor

Size	150	300	450	600
Cost	0.500	0.350	0.253	0.220
Size	750	900	1050	1200
Cost	0.276	0.183	0.228	0.170

4. Simulation Results

Simulation is carried on 11kV, IEEE-34 bus radial distribution network consisting of a main feeder, four laterals and has 4636.5 kW and 2873.5 kVAR total active and reactive load respectively. As the loading of the system increases deviation of bus voltage from base values becomes more and more prominent as shown in figure 1, the PV curve of IEEE-34 bus system. As explained in section 2.2, the VSF of all the buses is calculated and the strongest buses selected as candidate bus for CSs placement according to zone

are zone-1(2,3,13), zone-2(14,15,16), zone-3(5,6,7), zone-4(28,29,30) and zone-5(8,9,18).
Minimum and maximum value of voltage magnitude at each bus is limited to 0.90 p.u. and 1.10 p.u. respectively for all conditions in this work. Base case total active power loss, operating cost, minimum voltage magnitude and minimum value of VSI is 221.723 kW, \$37249.54, 0.942 p.u. and 0.7866 respectively.

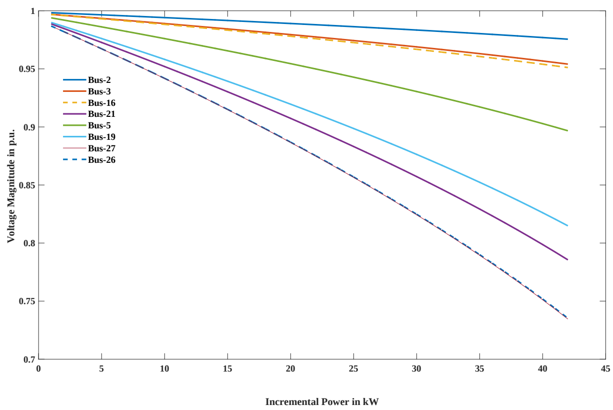

Figure 1: PV Curve of IEEE-34 bus system

Various cases are considered to demonstrate the suitability of the method and concept selected in this work as shown in table 3. Since, due to nature of objective function from each zone always minimum size of charging station is only selected by algorithm so in this work a limiting minimum value of total capacity of charging station (CS_{lim}^{min}) is set and results are obtained.

Table 3: Table showing various cases considered

Case	I	II	III	IV	V
CS_{lim}^{min}	0	900	1200	1400	1450

By using PSO optimization technique optimal sizing and placement of CSs is done in the IEEE-34 bus system with consideration of constant power load (CPL) model and constant power voltage dependent load (CPVDL) model, the results obtained are shown in table 4. Size and buses selected for charging station by PSO in each case to obtain optimum result is shown in table 5.
It can be seen from the table 4, with variation in limiting size the total capacity of CS also varies and accordingly the value of total active power loss and minimum value of voltage stability index of the selected system varies. Also, with consideration of CPVDL model of CS there is variation in power loss and other electrical parameters of the system as expected. For case III, the power loss decrease to 253.035 kW for CPVDL model from 255.122 kW for CPL model, which does not match with other case trend although total capacity of CS remains same equal to 1219 kW in both the cases. This is due to selection of size (position) = 655(2); 234(5); 119(8); 211(14) in case CPVDL model, which is different from CPL mode. Hence, it can be concluded that CPVDL model gives best result should be considered for planning purposes also.

Table 4: Charging Station Placement Details

Case	Power Loss in kW		Min. Value of VSI	
	CPL	CPVDL	CPL	CPVDL
I	240.531	240.735	0.7804	0.7804
II	244.475	244.694	0.7792	0.7792
III	**255.122**	**253.035**	0.7762	0.7766
IV	264.365	264.849	0.7732	0.7730
V	267.074	267.594	0.7724	0.7723

Table 5: Size and Buses selected for charging station placement

TCCS=Total Capacity of CS in kW		
Case	TCCS	Size in kW (Bus)
I	555	175(2); 142(5); 119(8); 119(14)
II	900	520(2); 142(5);119(8) ;119(14)
III	1219	655(2); 142(5); 211(8); 211(15)
IV	1401	655(2); 249(5); 226(15); 271(28)
V	1474	655(2); 289(5); 266 (14); 264 (29)

For all the cases, optimal placement and sizing of capacitor by PSO algorithm is done in presence of charging station with consideration of CPL model and the results obtained are shown in table 6. The size and bus selected for capacitor in the IEEE-34 bus system for each case is shown in table 7.

Table 6: Capacitor placement in presence of CSs

CS= With Charging Station, CAP_CS= With Capacitor in presence of Charging Station				
Case	Power Loss in kW		Min. Value of VSI	
	CS	CAP_CS	CS	CAP_CS
I	240.531	177.671	0.7804	0.8091
II	244.475	181.522	0.7792	0.8079
III	255.122	191.600	0.7762	0.8059
IV	264.365	200.646	0.7732	0.8027
V	267.074	203.290	0.7724	0.8019

From the table 6 it can be observed that with placement of charging station in each case the power loss and value of VSI gets degraded but after placement of capacitor power loss and value of VSI gets improved to a value even better than that of base case. Hence, showing advantage of capacitor placement in presence of charging station.

Table 7: Size and Buses selected for Capacitor placement in presence of CS

TCCap=Total Capacity of Capacitor in kVAR			
Case	TCCS	TCCap	Size in kVAR (Bus)
I	555	2400	600(10); 450(17); 450(19); 450(22); 450(26)
II	900	2400	600(10); 450(17); 450(19); 450(22); 450(26)
III	1219	2550	450(7); 450(11); 450(17); 600(21); 600(25)
IV	1401	2550	450(6); 600(10); 600(19); 450(22); 450 (26)
V	1474	2550	450(6); 600(10); 600 (19); 450(22); 450(26)

Table 8: Reactive power loss and voltage magnitude in presence of capacitor and CS

V_{min} = Minimum value of voltage magnitude of the system				
Case	Power Loss in kVAR		V_{min} in p.u.	
	CS	CAP_CS	CS	CAP_CS
I	71.364	52.857	0.940	0.948
II	72.962	54.422	0.939	0.948
III	76.496	57.763	0.939	0.947
IV	79.611	60.809	0.938	0.946
V	80.564	61.741	0.937	0.946

From table 6 and 8, it can be observed that after placement of charging station active power loss for case I to V increases by 8.48%, 10.26%, 15.06%, 19.23% and 20.45% respectively in compare to base case power loss value 221.723 kW and reactive power loss for case I to V increases by 9.61%, 12.06%, 17.49%, 22.27% and 23.74% respectively in compare to base case reactive power loss value 65.110 kVAR. After placement of capacitor active power loss in comparison to base case loss for case I to V decreases by 19.87%, 18.13%, 13.59%, 9.51% and 8.31% respectively while reactive power loss in comparison to base case reactive power loss for case I to V decreases by 18.82%, 16.42%, 11.28%, 6.61% and 5.17% respectively. It can be observed that from case I to V increase in size of CS is 919 kW, increase in total active power loss is 26.543 kW which is compensated by increase in size of capacitor from I to V case by 150 kVAR only. Thus, it is better to select the maximum total size of CS to be integrated in the network optimally according to the necessity as total increased power loss can be further reduced and improved to a certain limit.

Table 9: Voltage Magnitude in p.u.

Bus No.	Base	CPL	CPVDL	CAP_CS
1	1.0000	1.0000	1.0000	1.0000
2	0.9941	0.9927	0.9927	0.9937
3	0.9890	0.9868	0.9868	0.9889
4	0.9821	0.9790	0.9790	0.9821
5	0.9761	0.9723	0.9722	0.9764
6	0.9704	0.9663	0.9662	0.9713
7	0.9666	0.9617	0.9616	0.9671
8	0.9645	0.9596	0.9595	0.9652
9	0.9620	0.9571	0.9571	0.9630
10	0.9608	0.9559	0.9559	0.9620
11	0.9604	0.9555	0.9554	0.9615
12	0.9602	0.9553	0.9553	0.9614
13	0.9887	0.9861	0.9861	0.9882
14	0.9884	0.9853	0.9853	0.9874
15	0.9883	0.9852	0.9852	0.9873
16	0.9883	0.9852	0.9852	0.9873
17	0.9660	0.9618	0.9617	0.9675
18	0.9622	0.9581	0.9580	0.9644
19	0.9581	0.9539	0.9539	0.9610
20	0.9549	0.9506	0.9506	0.9580
21	0.9520	0.9478	0.9477	0.9555
22	0.9487	0.9445	0.9444	0.9526
23	0.9460	0.9418	0.9417	0.9501
24	0.9435	0.9392	0.9392	0.9478
25	0.9423	0.9380	0.9380	0.9468
26	0.9418	0.9375	0.9375	0.9464
27	0.9417	0.9374	0.9374	0.9462
28	0.9663	0.9610	0.9609	0.9664
29	0.9660	0.9604	0.9604	0.9658
30	0.9659	0.9603	0.9602	0.9657
31	0.9605	0.9556	0.9555	0.9616
32	0.9601	0.9552	0.9552	0.9613
33	0.9600	0.9551	0.9550	0.9611
34	0.9599	0.9550	0.9549	0.9611

Table 9 shows voltage magnitude in p.u. for base (with absence of capacitor and CS), CPL (in presence of CS with constant power load model), CPVDL (in presence of CS with constant power voltage dependent load model) and CAP_CS (in presence of both capacitor and CS) with total capacity 1474 kW of CS. With total capacity 1474 kW of CS, branch power flow, branch power loss and bus voltage magnitude is plotted to obtain the graph as shown in figure 2, 3 and 4 respectively. Reactive power loss and minimum value of voltage magnitude of the system is shown in table 8. From this table, it can be observed that in each case minimum value of voltage magnitude of the system gets improved to a value even better than base case value of 0.942 p.u., thus improving the overall system performance.

From figure 2, it can be observed that after placement of charging station and capacitor the power flow gets increased in compare to base case in the branches which lies in the path from node at which charging station or capacitor is placed to root or slack node.

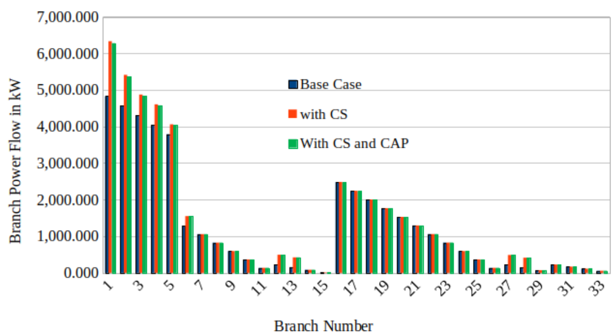

Figure 2: Branch Power Flow in kW

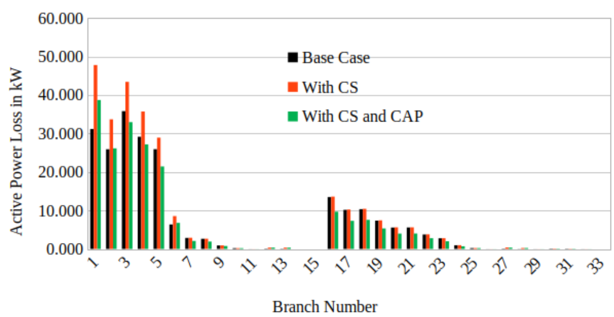

Figure 3: Branch Power Loss in kW

From figure 3, it can be observed that in each branch with placement of CS power loss gets increased but after placement of capacitor the branch power loss gets decreased thus reducing the operating cost of the system.

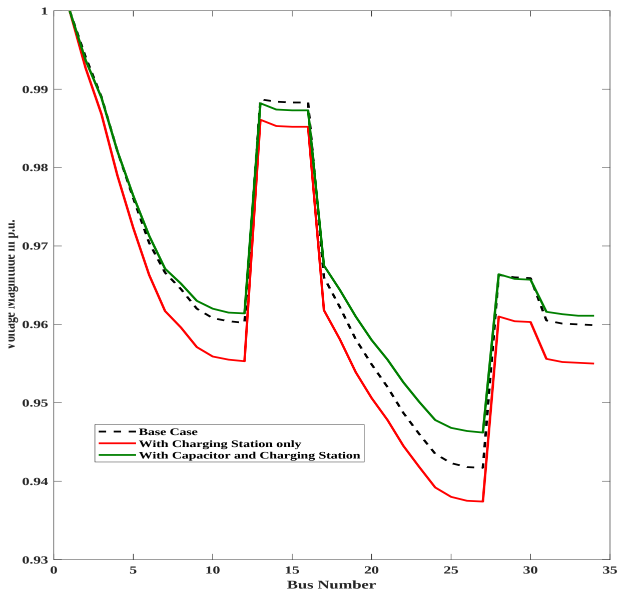

Figure 4: Voltage magnitude in p.u. of each bus

From figure 4, it can be observed that after placement of charging station voltage of each bus gets degraded but after placement of capacitor voltage magnitude of each bus gets improved to a value even better than base case.

5. Conclusion

The results obtained by implementing the proposed methodology on IEEE-34 bus radial distribution system in MATLAB environment demonstrate that the optimal placement and sizing of electric vehicle charging station follows the principle of selecting the positions nearer to the slack bus and the minimum size of the charging station among the candidate buses and sizes respectively as far as possible. On the other hand, the optimal placement and sizing of capacitor follows the principle of selecting the positions at the reactive power load centers and the farthest point from the slack bus of the hidden zones created on the basis of no. of capacitors to be placed and the sizing is selected on the basis of total kVAR rating of the reactive power load of the zones. The minimum size selection problem of CS can be improved by forcing the algorithm to select the total sizes of the charging station above a limiting minimum value as per the requirement under the acceptable voltage limit constraint. With increase in total size of CS, it can be concluded that there is increase in total active and reactive power loss and decrease in minimum value of VSI and voltage magnitude but these parameters of distribution network is restored to a value even better than base case after optimal allocation of capacitor. Thus, showing advantage of capacitor placement in the existing distribution system having charging station.

Hence this work will act as a platform for the power system engineers to maximize the charging station integration to the existing electric radial distribution network taking the benefit of facilities like capacitor, DG, reconfiguration etc. in near future.

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Appendix

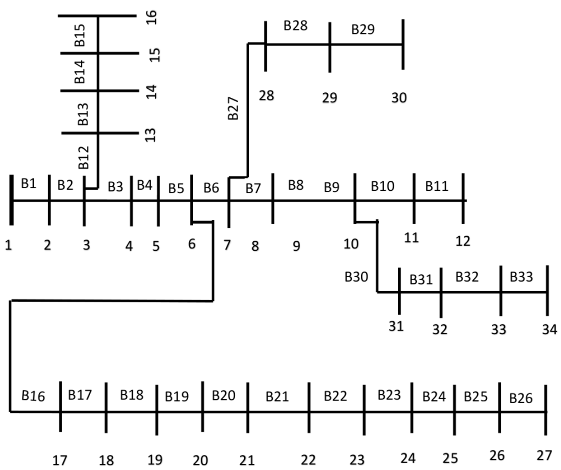

Figure 5: IEEE-34 Bus Electrical Radial Distribution Network