

Optimal Location Of EV Charging Station, Shunt Capacitor And DG In Radial Distribution Network

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Abstract: The increasing penetration of electric vehicles (EVs) and distributed generation (DG) into radial distribution networks creates new issues related to voltage stability, power loss, and load management. In response to these issues, this study is interested in the optimal placement of EV charging stations, DG units, and shunt capacitors to enhance the operational performance of the network. Metaheuristic optimization methods, namely Genetic Algorithm (GA) and Shuffled Frog Leaping Algorithm (SFLA) are utilized to find the best locations and sizes of these components subject to system constraints. The goal is to reduce total power losses and enhance voltage profiles throughout the distribution system. Comparative simulation outcomes reveal that the coordinated allocation method significantly outperforms uncoordinated methods, yielding higher efficiency and reliability. This paper provides a realistic solution to sustainable development and enhanced integration of EV and renewable energy technologies into radial distribution systems.

Keywords: Electric vehicle, distributed generation, genetic algorithm, shuffled frog leap algorithm, distribution system, optimization.

1. INTRODUCTION

The majority popularity of electric cars (EVs) has taken over the vision of the contemporary transport system, marked by a 57% increase in the yearly sales of EVs. As many as 1.1 million passenger EVs were sold worldwide in 2017 alone, and both on-road EVs and plug-in hybrid electric vehicles (PHEVs) had more than 3 million [1]. Some nations have announced their commitment to fully electrify their transport infrastructure by 2030. Increasing global warming and climate change have made policy-makers worry more about greenhouse gas (GHG) emissions, for which the transport sector is responsible for 23% of total GHG emissions globally [2]. Hence, it is impossible to reach the target of curbing global warming without extensive change in the transport sector. Vehicle electrification, through the use of low or zero-emission EVs, becomes an imperative solution [3].

To be capable of withstanding the increasing level of global pressure, effective and reliable charging infrastructure is more crucial than ever. Electric Vehicle Charging Stations (EVCS), Distributed Generation (DG) units, and shunt capacitors will be at the center of frictionless integration of EVs with the power distribution grid [4]. With increasing volumes of EVs, increased demand for increased capacity and coverage of EVCS, especially in radial distribution networks, is needed to enhance the reliability, reduce range anxiety, and ensure grid stability [5].

The best location of Electric Vehicle Charging Stations (EVCS), Distributed Generation (DG) units, and shunt capacitors in radial distribution systems has been a matter of growing interest with the increasing use of electric vehicles (EVs) and distributed energy resources. Their best integration is very crucial to maintain grid stability, reduce power losses, and control voltage profiles within acceptable limits [6].

Ideal Location of EVCS: Sharma et al. [7] mentioned that random deployment of EVCS will cause network voltage instability and overloading. Ghosh et al. [8] presented a multi-objective optimization model by Genetic Algorithms (GA) for EVCS location selection with respect to grid constraints as well as customer convenience. Li et al. [9] gave a probabilistic model to embody the randomness in EV charging pattern to guarantee the reliability of EVCS location planning.

Integration of DG Units: Acharya et al. [10] introduced an analytical approach to DG allocation in order

to reduce network losses and enhance voltage stability. Hung et al. [11] presented a hybrid method by combining Analytical and PSO methods for optimal DG placement based on load fluctuation and DG characteristics like the intermittency of renewable energy.

Installation of Shunt Capacitors: Grainger and Lee [12] first proposed loss reduction models based on capacitor placements, which were extended later by Baran and Wu [13], who provided heuristic and optimization techniques for reactive power compensation. The most recent work discusses metaheuristic techniques such as Ant Colony Optimization (ACO) and Improved PSO for capacitor placement.

Parallel Installation of EVCS, DG, and Capacitors: Rani et al. [14] introduced a GA-based method for the simultaneous placement of EVCS, DGs, and capacitors in radial distribution systems. Bhatti et al. [15] presented a GA and ANN-based hybrid technique for collaborative optimization with improved power quality and losses. In addition, Sultana and Mustafa [16] used the SFLA algorithm for joint allocation of DGs and capacitors with varied loading patterns.

Metaheuristic Optimization Techniques: GA and SFLA metaheuristic algorithms have been utilized to optimize successfully the nonlinear, combinatorial optimization problem of joint placement of EVCS, DG, and capacitor units. Eusuff et al. [17] and Goldberg [18] explained how these algorithms balance local and global search with high ability to escape local minima and converge to optimal solutions.

Summary: Literature supports that a general agreement is there about the need for joint placement of EVCS, DG units, and capacitors to facilitate radial distribution network operation in the presence of increasing EV penetration. However, existing research gaps in addressing uncertainties like dynamic EV loads, variability of renewable generation, and reconfigurations of the network in a holistic way are there, which indicates the need for effective metaheuristic models like hybrid GA-SFLA models.

This study considers EVCS, DG, and capacitor location, all of which are highly influenced by the provided grid topology, loading scenario, and network constraint. 20–30% power loss in some network structures can be reduced by optimizing EVCS location, DG units, and capacitors in conjunction with sophisticated optimization methods.

Also, the extreme time-of-day volatility in demand, particularly from EV charging and intermittent DG sources (such as solar PV), will probably require advanced planning measures for seamless integration into cities and suburbs. Most of the optimization strategies recommend EVCS installation near substations, along highways, or in sparse residential areas, while DG units should be positioned closer to the load centers to feed the local load, and capacitors are positioned where they can maintain voltage stability and reduce reactive power losses.

2. Problem Formulation

2.1 Electric Vehicle Charging Stations (EVCS)

Electric Vehicle Charging Stations (EVCS) are specialized facilities utilized for providing electric power for recharging electric vehicles and can be incorporated into household, commercial, and public grids. EVCS charging stations are defined by charging speed into three categories: Level 1 (slow charging), Level 2 (medium-range charging), and DC Fast Charging (fast charging). Future rollout of EVCS, especially in urban and suburban areas, is crucial in addressing increasing demands for electric vehicle support. Proper planning not only facilitates the expansion of the expanding EV fleet but also mitigates operational pressure on the power supply grid, increases accessibility, and alleviates range anxiety for EV customers.

2.2 Distributed Generation (DG)

Distributed Generation (DG) is small-scale power generation technologies, often renewable-based (solar PV, wind turbines), connected directly to the distribution network. DG has numerous advantages:

- **Voltage Support and Loss Minimization:** Properly placed DG units can assist in voltage support at local levels and reducing system power losses.
- **Challenges:** DG unit placement can lead to reverse power flows, voltage rise problems, and protection system issues. Therefore, it is important to optimize DG location and sizing for maximum benefits and prevention of operational problems.

2.3 Shunt Capacitors

Distribution-grade shunt capacitors are traditionally used in the distribution system in order to boost the power factor, reduce the real and the reactive losses and voltage stabilization:

- **Voltage Profile Improvement:** Capacitor provides local source of reactive supply of power improving the remote bus voltage.
- **Loss Minimization:** Capacitors reduce system loss by reducing the circulating of reactive currents.

- Challenges: Overcompensation by capacitors may lead to overvoltage conditions, especially during light load periods. Therefore, optimal placement and sizing are crucial for maximum network benefit.

2.4 Load Flow Analysis

The backward-forward sweep algorithm combines graph traversal methods and power flow computation to calculate voltages and currents in the network.

- Backward Sweep: Backward sweep begins at end nodes (loads) and goes towards the root (substation). The process determines the current at each node during this step by employing the branch voltage and branch impedance.
- Forward Sweep: Once the calculation of currents in the backward sweep, the forward sweep re-calculates the node voltages based on line and load power consumed.

Algorithm for Backward-Forward Sweep Method involved are:

- Initialization: Begin with an initial voltage estimate of the node voltages (the substation voltage is usually known).
- Backward Sweep: Compute the currents at each load node, from the network end to the source, from the new voltage values of the previous iteration.

$$I_L = (P_L - jQ_L)/V^* \quad (1)$$

- Forward Sweep: With known currents, compute the new voltage values at each node, using the power flow equations and the impedance of the distribution line.

$$I_B = I_L + \sum I_p \quad (2)$$

$$V_n = V_m - I_B Z_B \quad (3)$$

- Iteration: Repeat (iterate) until node voltages converge within a satisfactory tolerance

2.5 Radial Distribution Networks

Radial distribution systems are a typical power supply setup with one-way power supply from a single substation to multiple end-users. Radial systems are simple to design but are highly susceptible to load and generation fluctuations. Placement of Electric Vehicle Charging Stations (EVCS) and installation of Distributed Generation (DG) sets and shunt capacitors should be properly planned to obtain well-balanced power supply, optimum load management, and stable voltage. Otherwise, the additional load of EVs will lead to network congestion, increased voltage sag, increased technical losses, overloading of transformers, and inefficiency of the system.

2.6 Optimization Techniques:

2.6.1 Genetic Algorithm (GA):

GA is a robust nature-inspired optimization technique, simulating the natural selection process. It is well suited to large-scale complex placement problems with multiple objectives such as loss minimization, voltage stability improvement, and network upgrade reduction while installing EVCS, DG, and capacitors together.

- Voltage Stability Enhancement: Voltage stability is critical to the provision of stable service in the grid. GA can be employed to determine the optimal placement of voltage support equipment (such as capacitors and DGs) to improve the voltage profile along the network, minimizing the risk of voltage instability or blackouts.

GA operates on a series of steps:

- Selection: Solutions of the existing population are selected according to their level of fitness, and more fit solutions have a better chance of being selected.
- Crossover (Recombination): Two solutions (parents) are crossed over to create new solutions (offspring), simulating the genetic crossover operation.
- Mutation: Random modifications are applied to some solutions for injecting diversity and avoiding getting stuck in local minima.
- Evaluation: The appropriateness of the next generation of solutions is evaluated relative to objectives established earlier.

2.6.2 Shuffled Frog Leaping Algorithm (SFLA):

- Shuffled Frog Leaping Algorithm (SFLA) is an efficient optimization technique that draws inspiration from the social foraging behavior of frogs. The concept is to simulate the manner in which frogs search for food in an environment. Frogs

move around together, share information, and gain experience to find the most favorable source of food. In SFLA, the population of solutions (frogs) is employed to search in the solution space, and the frogs perform local search and global information exchange. Combining these two aspects helps to improve the exploration of diverse solutions and to evade local optima.

- The algorithm continues to iterate through a series of steps: Initialization: The process begins by setting a starting population of frogs (solutions). Each frog is assigned a location that is a possible solution to the problem to be optimized.
- Evaluation: Every frog assesses the quality of its solution by calculating an objective function (fitness function). It can be related to various objectives such as loss minimization, voltage stability, or network efficiency for a distribution system.
- Local Search: For every frog, there exists a local search in the immediate neighborhood. The aim is to attempt to advance the solution from where it currently stands. The frog adjusts its position slightly in order to improve the fitness of its solution.
- Global Search: After local search, frogs exchange the best solutions discovered by other members of the population. Global search mimics the social interaction whereby frogs talk about food sources. Frogs nearest to improved solutions are most likely to persuade other frogs to improve their own solutions.
- Shuffling: At a fixed number of iterations or at regular intervals, the frogs are shuffled into new groups. Shuffling guarantees that the frogs are exposed to diverse solution spaces, thus promoting diversity and preventing the algorithm from converging to suboptimal solutions prematurely.
- Convergence: Iteration continues until convergence criteria is reached, usually when a specific number of iterations is obtained or when the fitness improvement is less than a minimum value

3. SOLUTION METHODOLOGY

3.1 Problem solving using Genetic algorithm

The optimal placement of EVCS, DG and Capacitor bank are done using genetic algorithm (GA) and shuffled frog leap algorithm (SFLA) in this paper. The procedure to solve the problem using GA is explained using the flowchart given in Fig.1. In this approach the population size is taken as 40. A string length of 22 bits is used, among which the first 4 bits are used for considered for location of DG, the next 6 bits are considered for size of DG, further next 6 bits are used for capacitor size and the last 6 bits are used for size or capacity of EVCS. The location of capacitor is based on the value of quadratic expression $b^2 - 4ac$, where a, b and c constants are evaluated by taking the real and reactive power injections at a bus. The problem using this method is solved with suitable value of tolerance until all the strings in the population give the same fitness within tolerance.

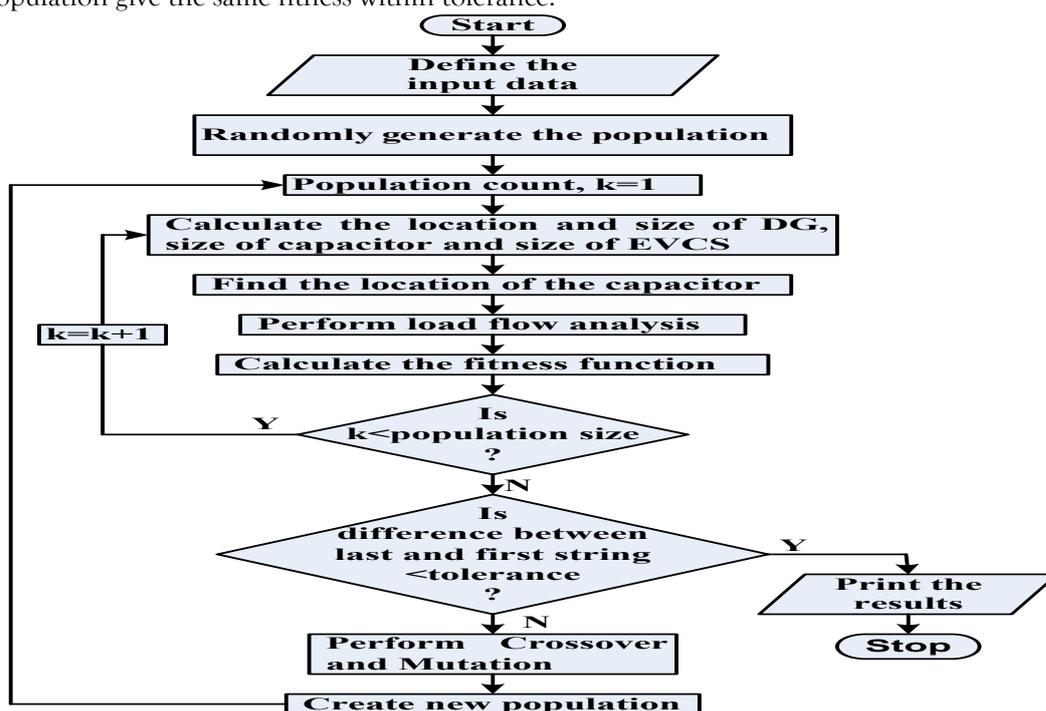


Fig.1: Flowchart for Optimal Location of EVCS, DG and Capacitor Using Genetic Algorithm

3.2 Problem solving using Shuffled frog leap algorithm

In this method the population size is same as genetic algorithm, that is 40. Here the concept of frogs is used instead of population. 40 frogs are divided into 4 memeplexes, each memeplex containing 10 frogs. The location and size of DG, capacitor size and EVCS size are calculated using this approach. The local and global best values are used to generate new population as:

$$X_{new1} = X_{old} + r_1 * (\text{local best} - X_{old}) \quad (4)$$

$$X_{new2} = X_{new1} + r_2 * (\text{global best} - X_{new1}) \quad (5)$$

The location of capacitor is calculated in the same manner as it is calculated using genetic algorithm. The detailed view of the algorithm is provided in flowchart of this algorithm in Fig. 2.

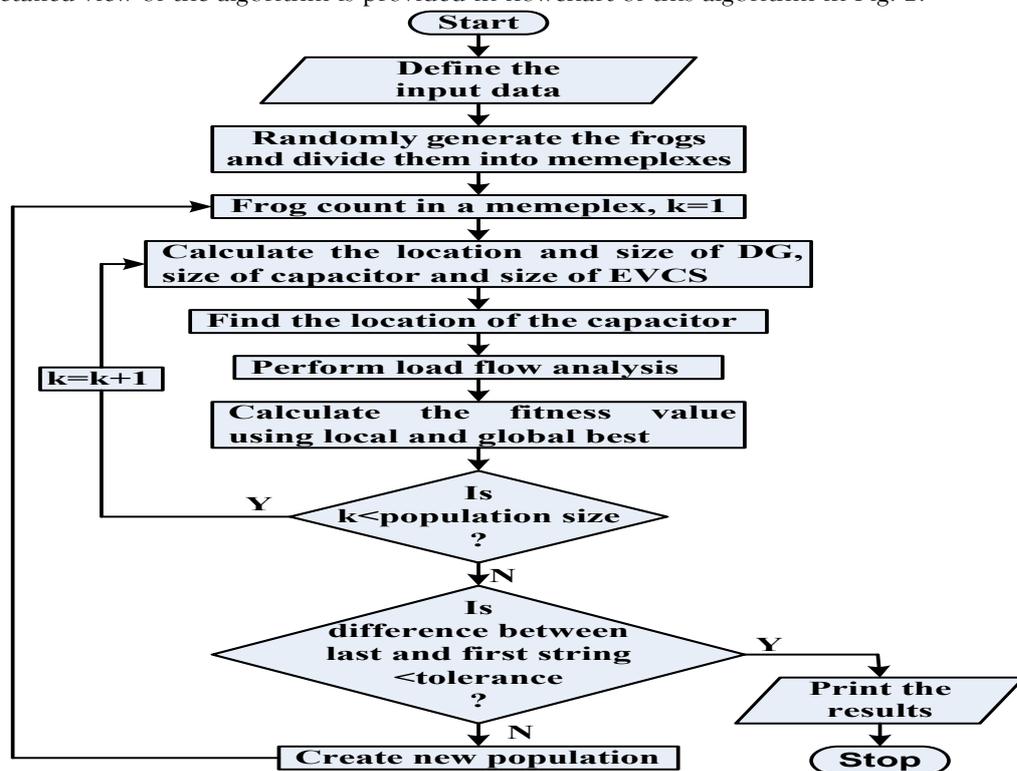


Fig.2: Flowchart for Optimal Location of EVCS, DG and Capacitor Using Shuffled Frog Leap Algorithm

4. Result Analysis

This section of the paper includes the results of different case studies, when both the algorithms are applied to 15-Bus as well as 33-Bus Systems. Consider the single line diagrams of the both networks mentioned as Fig.3 and Fig. 8 along with input data of each system [19].

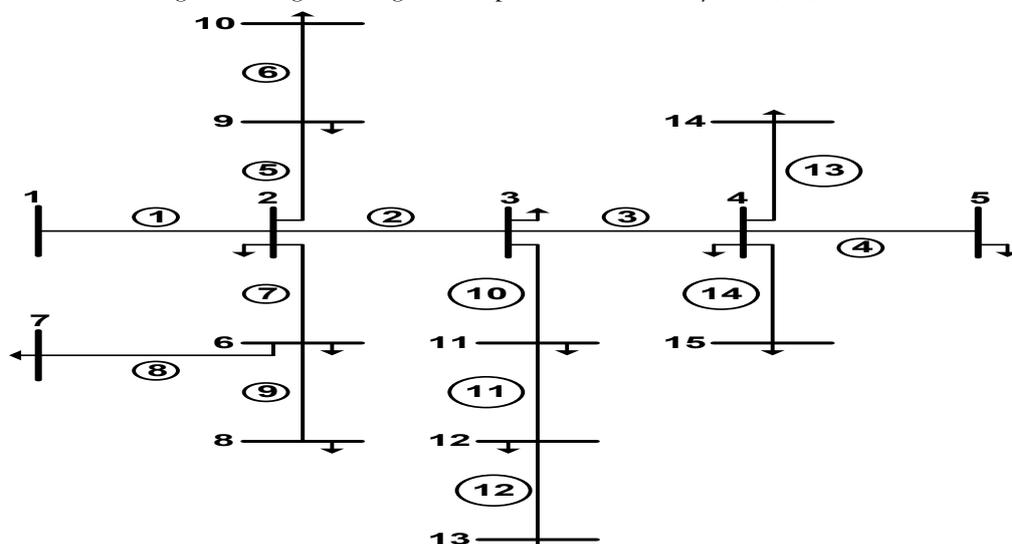


Fig.3: Single Line Diagram of 15-bus Radial Distribution Network

4.1 Result for Base Case Load Flow Analysis for 15-bus system

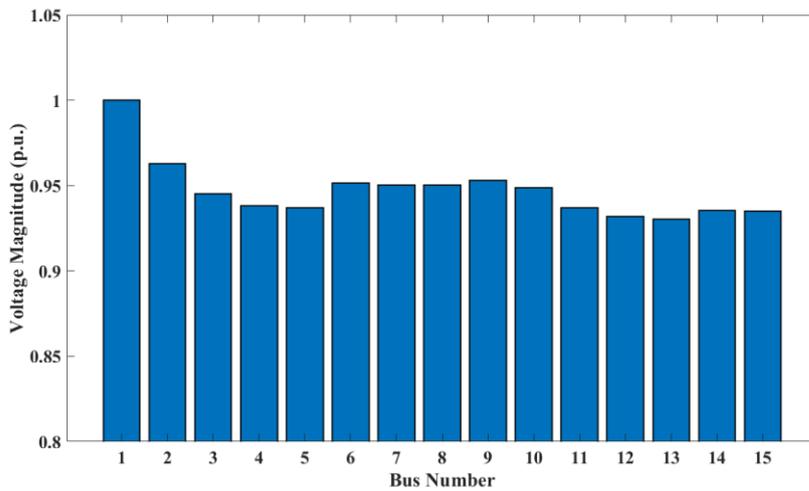


Fig. 4: Bus Voltages for Base Case Load Flow Analysis for 15-Bus System.

The total active power is 1296 KW and reactive power is 1315 KVAR. Total Real Power Loss is 65.8 KW and the minimum bus voltage is 0.9427 at bus number 13

4.2 Result for EVCS Installation using GA for 15 Bus System

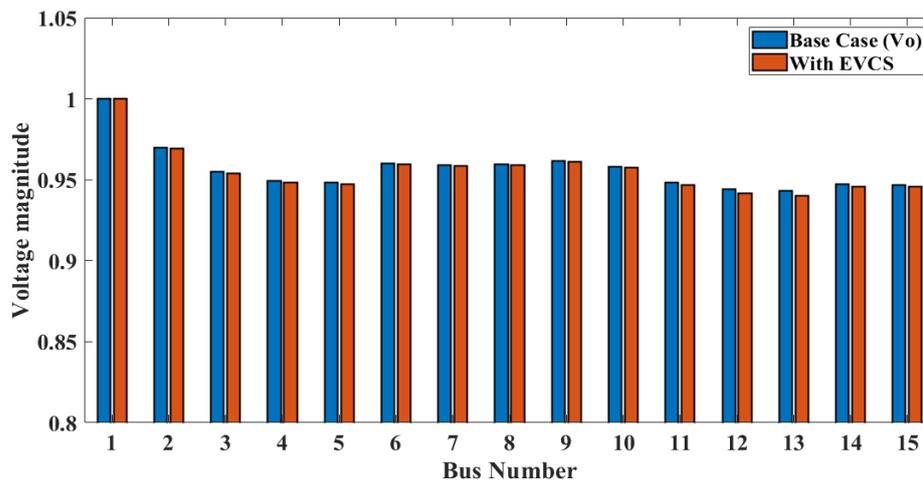


Fig. 5: Bus Voltages for EVCS Installation using GA for 15-Bus System.

The installation of EVCS will give a rise in the power loss as it acts as a load. The loss is 66.1 kW which is 0.45% more than the base case load flow analysis. The minimum voltage of this system is 0.9309 which is at bus number 12.

4.3 Results for Installation of EVCS and Capacitor using GA for 15-bus system

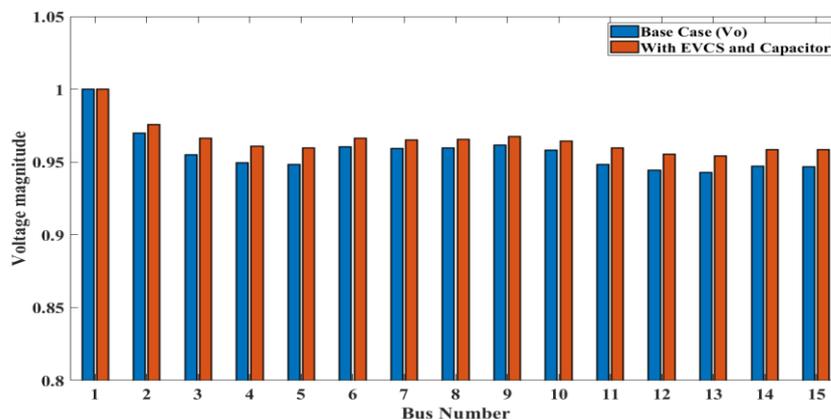


Fig. 6: Bus Voltages for Installation of EVCS and Capacitor using GA for 15-Bus System.

The loss in the power is reduced to 46.4 KW with minimum voltage of 0.9527 at bus number 13. Even though EVCS acts as an additional load to the network, the capacitor will compensate the drop in the voltage by supplying reactive power and improves the voltage profile and also reduces the active power loss.

4.4 Results for Installation of EVCS, Capacitor and DG using GA for 15-bus system

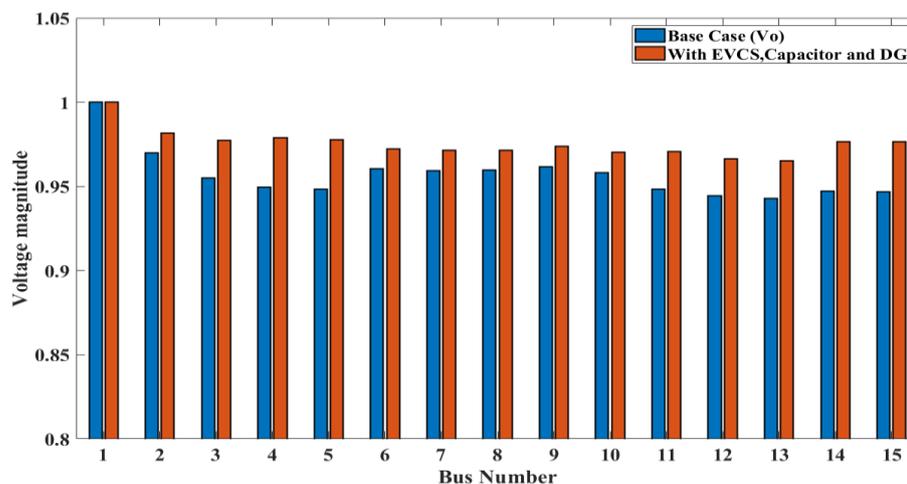


Fig. 7: Bus Voltages for Installation of EVCS, DG and Capacitor using GA for 15-Bus System.

Table 1: Comparative Analysis of all the Cases for 15 Bus System using GA

| | Base Case | With only EV | With EV and Capacitor | With EV, DG and Capacitor |
|---|------------------|------------------|-----------------------|---------------------------|
| Minimum Voltage | 0.9427 at Bus 13 | 0.9309 at Bus 12 | 0.9527 at Bus 13 | 0.9677 at Bus 13 |
| Power Loss (KW) | 65.8 | 66.1 | 46.4 | 29.8 |
| Percentage of Power Loss w.r.to Base case | | 101.45% | 70.5% | 45.2 |

The loss in the power is further reduced to 29.8 KW with minimum voltage of 0.9667 at bus number 13. Even though EVCS acts as an additional load to the network, the capacitor and DG installed will compensate the drop in the voltage by supplying reactive power and improve the losses by supplying active power respectively.

Table 2: Location and size of EVCS, DG and Capacitor for 15-bus system

| | EVCS | Capacitor | DG |
|----------|----------|-------------|-----------|
| Location | 12 | 3 | 3 |
| Size | 43.01 KW | 521.96 KVAR | 378.62 KW |

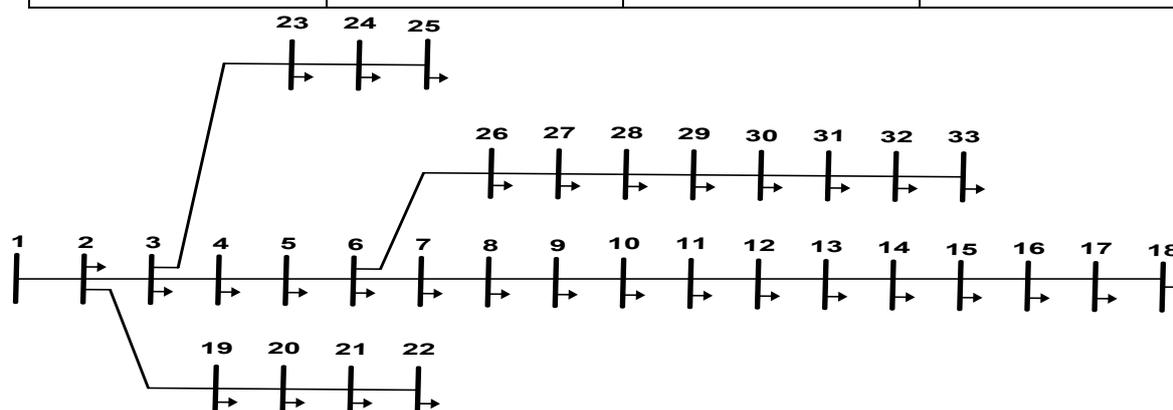


Fig.8: Single Line Diagram of 33-bus Radial Distribution Network

4.5 Results for Base Case Load Flow Analysis for 33-bus system.

The total active power is 3715 KW and reactive power is 2300 KVAR. Total Real Power Loss is 283.4 KW and the minimum bus voltage is 0.8797 at bus number 19.

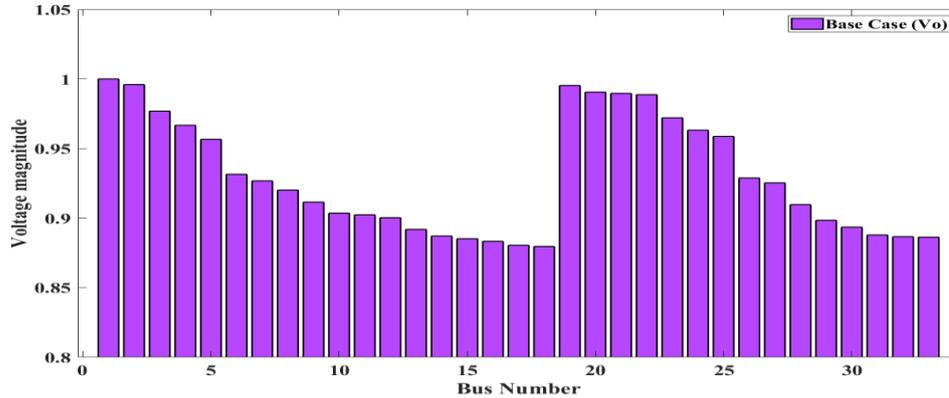


Fig. 9: Bus Voltages for Base Case Load Flow Analysis of 33 Bus System

4.6 Results for EVCS Installation using GA for 33 Bus System

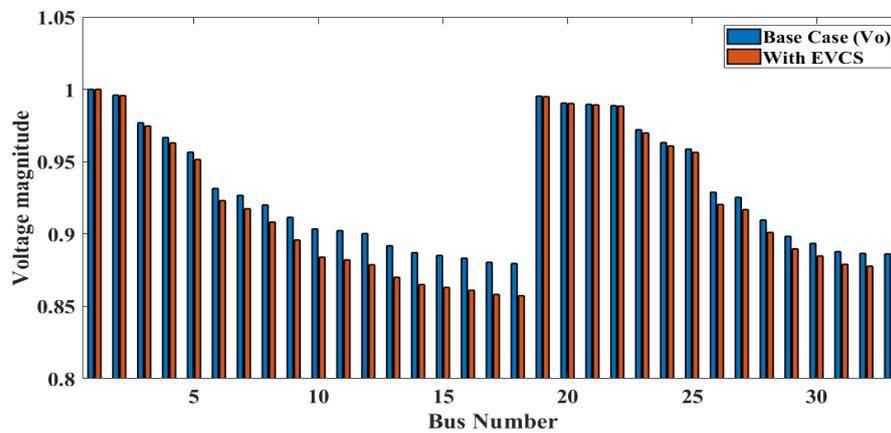


Fig. 8: Bus Voltages for EVCS Installation using GA for 33 Bus System

The installation of EVCS will give a rise in the power loss as it acts as a load. The loss is 284.7 KW which is 0.45% more than the base case load flow analysis. The minimum voltage of this system is 0.8717 which is at bus number 19.

3.7 Result for Installation of EVCS and Capacitor using GA for 33-Bus System

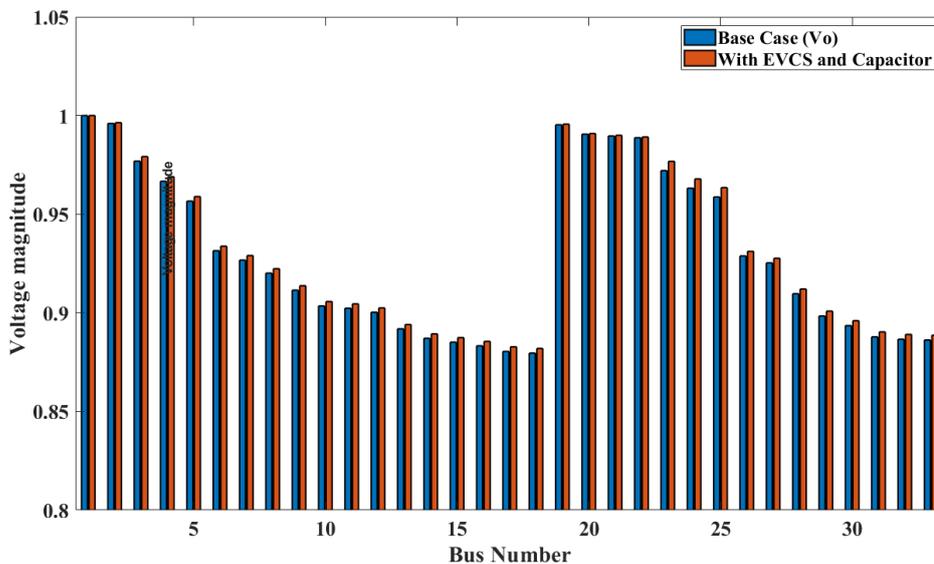


Fig. 9: Bus Voltages for Installation of EVCS and Capacitor using GA for 33-Bus System.

The loss in the power is further reduced to 266.7 KW with minimum voltage of 0.8818 at bus number 18. Even though EVCS acts as an additional load to the network, the capacitor will compensate the drop in the voltage by supplying reactive power and improves the voltage profile and also reduces the active power loss.

3.8 Result for Installation of EVCS, DG and Capacitor using GA for 33-Bus System

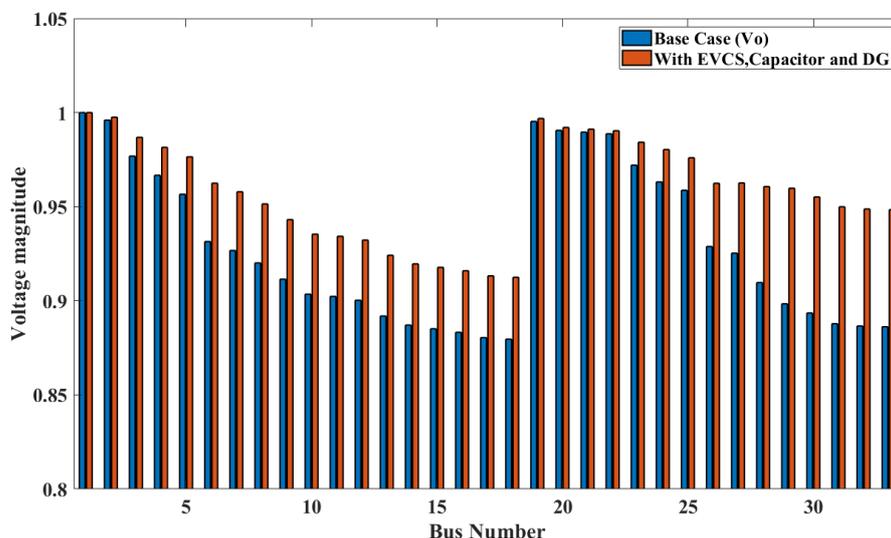


Fig. 10: Bus Voltages for Installation of EVCS, DG and Capacitor using GA for 33-Bus System.

The loss in the power is further reduced to 149.1 KW with minimum voltage of 0.9085 at bus number 33. Even though EVCS acts as an additional load to the network, the capacitor and DG installed will compensate the drop in the voltage by supplying reactive power and improve the losses by supplying active power respectively.

Table 5: Comparative Analysis for all the cases for 33 Bus System using GA

| | Base Case | With only EV | With EV and Capacitor | With EV, DG and Capacitor |
|---|------------------|------------------|-----------------------|---------------------------|
| Minimum Voltage | 0.8797 at Bus 19 | 0.8717 at Bus 19 | 0.8818 at Bus 18 | 0.9086 at Bus 33 |
| Power Loss (kW) | 283.4 | 284.7 | 266.7 | 149.1 |
| Percentage of Power Loss w.r.to Base Case | | 101.45% | 94.1% | 52.6% |

Table 6: Location and size of EVCS, DG and Capacitor.

| | EVCS | Capacitor | DG |
|----------|----------|-------------|------------|
| Location | 16 | 23 | 8 |
| Size | 79.19 KW | 846.96 KVAR | 1123.32 KW |

5 CONCLUSION

The outcomes indicate that proper siting and sizing of the units reduce the adverse effects usually observed with high EV loads, such as increased losses and voltage drops. DGs provide site-local generation support, reducing dependency on the upstream network, while capacitors provide reactive power compensation for improved voltage profiles. They work together to develop the synergistic effect that optimizes the system's efficiency of operation.

Location of Electric Vehicle Charging Stations (EVCS), Distributed Generators (DGs), and capacitors in a radial distribution system at their optimal locations is crucial in order to enhance the overall efficiency,

reliability, and performance of power networks. In this work, it is demonstrated that if an appropriate optimization technique, e.g., a Genetic Algorithm (GA), is applied, it is possible to significantly enhance voltage stability, decrease power loss, and load balancing. By considering coordinated installation of EVCS, DGs, and capacitors, the distribution system is better able to cope with rising energy demand due to EV penetration as well as to ensure that voltage limits on all buses are satisfied.

In addition, putting it side-by-side with other scenarios without EVs or even without coordinated placement clearly illustrates the necessity of a combined planning process. The advocated solution not only promises technical but also economic gains by reducing system losses and hopefully postponing system upgrade expenses. Overall, strategic and simultaneous installation of EVCS, DGs, and capacitors is essential to make power distribution networks future-proof. The technology makes it possible to integrate electric mobility and distributed energy resources on an inclusive basis and opens the way to a sustainable and resilient power grid.

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