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Cost Minimization in Radial Distribution System Integrated with Commercial Electric Vehicle Charging Station †

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Abstract: Energy-efficient modes of transportation have become essential today due to environmental challenges. However, utilities and decision-making bodies are reluctant to proceed in this direction because of the expected system instability. This paper contributes to minimizing the cost incurred due to energy losses in an IEEE-37 bus system integrated with a commercial electric vehicle charging station (EVCS) located in Qatar. The Particle Swarm Optimization (PSO) algorithm is used for the efficient location allocation of EVCS. The system is analytically examined through the Thukaram Load Flow Algorithm and investigations are conducted to observe the beneficial impacts of load balancing between RES and utility.

Keywords: electric vehicles; smart grid; cost minimization; renewable energy; metaheuristic algorithm; particle swarm optimization algorithm

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1. Introduction

The depletion of natural resources and the poisonous emissions from conventional vehicles have a detrimental role in environmental pollution. The trend in the electrification of the transport sector has grown substantially due to the augmented interest in the replacement of fossil fuels [1]. However, this will cause an overwhelming surge in the electricity demand. To prevent aggravation in this condition, imperative decisions must be made for electric vehicle charging stations (EVCS) to ensure minimum impact on the power grid and the environment [2]. This non-linear load not only impacts the voltage profile of the existing distribution system but also deteriorates the power quality delivered to other consumers in the system [3]. Therefore, this paper especially focuses on implementing the Particle Swarm Optimization (PSO) algorithm to cater for this issue. Section 2 explains the techniques developed to date to facilitate optimal planning and placement of EVCS. Section 3 discusses the mathematical problem formulation and the constraints imposed, whereas the results obtained after the implementation of PSO are evaluated in Section 4.

2. Literature Review

With the advent of electric vehicles (EVs), researchers have investigated in multiple dimensions to modify the existing power system. Harries Hawk Optimization and Teaching–Learning Based Optimization were implemented on the IEEE-33 bus and IEEE-69 bus systems to allocate EVCS in [4]. Likewise, Cuckoo Search Algorithm, Genetic Algorithm and Simulated Annealing Algorithm were employed for photovoltaic (PV) systems and EVs on an IEEE-33 bus system [5]. Furthermore, investigations were also conducted to ensure profit maximization and cost minimization by employing hybrid Crow Search Algorithm incorporated with a renewable energy source and battery energy storage system [6], Artificial Bee Colony algorithm and Firefly algorithm [7]. Alongside multiple algorithms, research to date also encompasses cost-based models, primarily focusing on minimizing investment cost [8], installation cost [9], charging cost [10] and penalties imposed for violating grid constraints [11]. Variations have also been observed in the work of various researchers in terms of constraints, such as the restrictions on the SOC of battery [12] and branch currents [12], along with equality and inequality constraints on the active and reactive power in the system [13,14].

However, this paper integrates optimal planning of EVCS in an IEEE-37 bus system with load balancing between the utility and solar PV system. A commercial, level 3, charging station in Qatar was considered, which has a minimum charging time of 20 min [15]. The load profile of this station is presented in Figure 1.

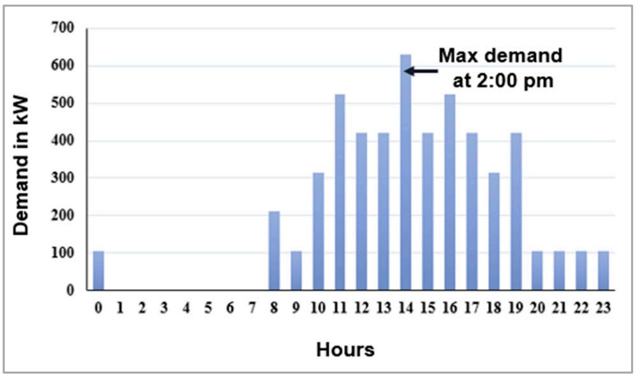

Figure 1. Load profile of commercial EVCS [15].

Furthermore, for efficient cost minimization, a feasibility study on the solar resources of Qatar was conducted. Maximum and minimum power outputs throughout the year were analyzed through the PV Watts calculator from the National Renewable Energy Laboratory. It was concluded that a solar PV system of 400 kW can bear 47.6% of the total load of this EVCS. Therefore, this paper discusses three cases in total, summarized in Table 1.

Table 1. Summary of case studies.

Cases	Considerations	Analytical Aspects
Base Case	Base Load on IEEE-37 Bus System	Voltage Profile, Active Power Losses
Case I	100% additional load of EVCS	Cost per unit of power loss, Voltage
Case II	53% additional load of EVCS	Profile, Active Power Losses

3. Problem Formulation

3.1. Objective Function

The primary objective of this paper is to place the commercial EVCS at an optimal location in the IEEE-37 bus radial distribution system, in accordance with the minimum cost incurred due to energy losses. This is considered to be 0.092 USD/kWh [16]. Power loss is calculated using Equation (1) [17].

$$\text{Power loss} = \sum |I|^2 R \tag{1}$$

Equation (2) is used to find the energy loss in a day.

$$\text{Energy loss} = \frac{\text{Power loss}}{\text{Time}} = \frac{\sum |I|^2 R}{24} \tag{2}$$

Since the cost incurred per unit of energy loss is 0.092 USD/kWh [16], the total cash outflow for the power loss in a day is calculated using Equation (3). This objective function is fed to the PSO algorithm to locate the most feasible location.

$$\text{Total Cost} = 0.092 \times \frac{\sum |I|^2 R}{24} \tag{3}$$

3.2. Constraint

Equation (4) shows that the voltage must lie within the range of ±5% [18].

$$0.95 \leq V \leq 1.05 \tag{4}$$

4. Results

This section of the paper highlights the outcomes when the problem statement in Section 3 was implemented using the PSO Algorithm. For better understanding, Section 4.1 discusses the effect of concentrated and distributed load in the IEEE-37 bus radial distribution system by employing the Thukaram Load Flow Algorithm (TLFA). In Section 4.2, the optimal location for the commercial EVCS is determined.

4.1. Power Flow Analysis on IEEE-37 Bus System

The initial load on the IEEE-37 bus system encompasses all sorts of consumers, be it residential, industrial, or commercial. [19]. The buses are not distinguished based on the nature of the load while performing the preliminary load flow analysis using TLFA. A mathematical model of the 37-bus system was developed in MATLAB R2018a. The base apparent power and the base voltage of the system were assumed to be 100 MVA and 12.66 kV, respectively. To ensure precision, the convergence criteria were defined as 1×10^{-4}. The bus data and line data for the system were taken from [19]. Figure 2 represents the 37-bus system under consideration.

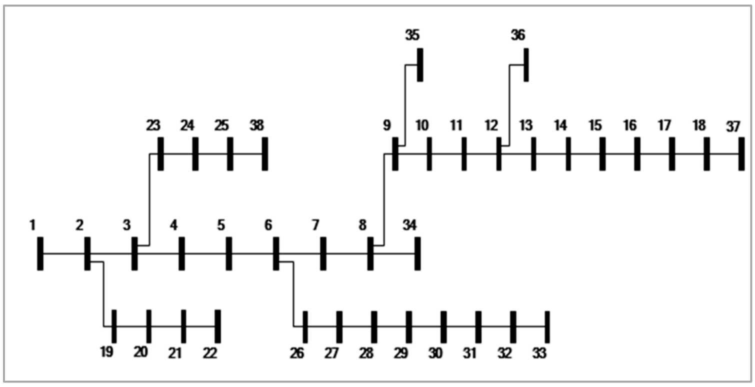

Figure 2. IEEE 37 Bus System [19].

However, while diving deeper into the research, these buses are classified according to the nature of the consumer as residential, industrial, and commercial. Load flow analysis (LFA) is performed once again to investigate the potential differences. Active load, reactive load, node voltages, and branch currents were obtained as results after the analysis of the system, with respect to concentrated load and load distributed into residential, industrial, and commercial. Table 2 summarizes the results obtained by treating the load as concentrated and then distributed.

Table 2. Results from Power Flow Analysis.

Parameters	Concentrated Load	Distributed Load
Minimum Voltage	12.649 kV	12.649 kV
Active Power Losses	1.8 kW	1.8 kW
Reactive Power Losses	1.2 kVA	1.2 kVA
Voltage Profile	1.51×10^{-4} kV	1.51×10^{-4} kV

4.2. Optimal Location for Complete Electric Vehicle Charging Station Load

Load of the EVCS was then placed on a commercial bus in the IEEE-37 bus radial distribution system using the PSO Algorithm. Here, the load of the EVCS was placed according to the case studies proposed in Table 1. LFA is then performed on the system and the bus, which provides the minimum value of the cost associated with energy losses, allocated to the charging station. The PSO algorithm determined commercial Bus 19 to be the optimal location in both cases.

Major changes in the fitness value of objective function were observed when the commercial load of EVCS placed on Bus 19 in the system was reduced to 53%. The cost incurred in the system due to energy losses can be observed in Figure 3. The difference between the expenditures with and without the solar PV system account for a difference of approximately 29%.

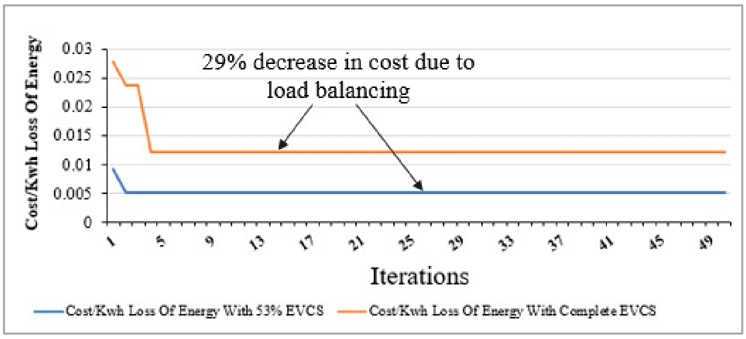

Figure 3. Comparison of cash outflows showing cost minimization.

Figure 4 represents that the voltage profile satisfies the constraint defined in Section 3.2. It can be seen that the initial load on the IEEE-37 bus system was slightly unbalanced, as the voltages fluctuate beyond the threshold. However, increasing the load on the optimal bus improved the system's voltage profile. On a further decrement in load, the fluctuations in the voltage further reduced and indicate increased system stability.

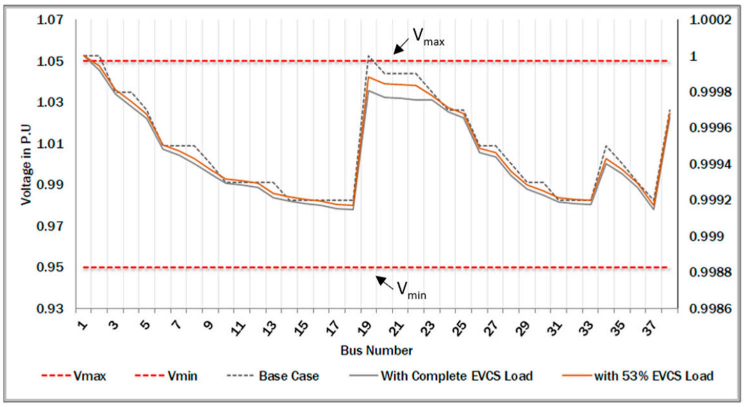

Figure 4. Comparison of Voltage Profile.

Figure 5 shows a spike in active power losses in the connecting branch of Bus 2 and 19 when the load of EVCS was placed on commercial Bus 19. These losses were then reduced up to 70% when a solar energy system was incorporated.

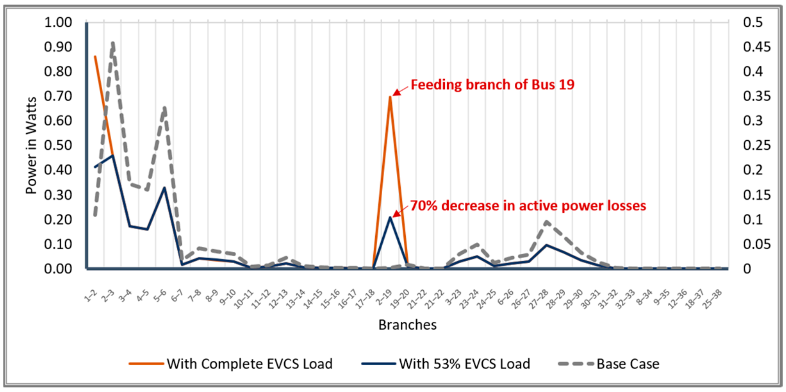

Figure 5. Comparison of Active Power losses with 70% decrease after integrating solar PV system.

5. Conclusions

This paper considers the probable practical solutions that can be effectively implemented while planning electric vehicle charging stations. The paper determined the most suitable location to be allocated to a commercial EVCS by using the Particle Swarm Optimization (PSO) algorithm. In the research, the total cost incurred due to energy loss was minimized by **29%** when load balancing was performed between the utility and solar photovoltaic system. Furthermore, a **70%** decrease in power loss was observed by employing the said technique. This paper successfully contributed to the financial gains of the utility and the consumer, while maintaining the voltage stability of the system. The expenditures were observed to reduce to a considerable extent, which can impact the cost per unit of energy charged from the customers. The research plays a pivotal role in minimizing the overhead charges because of the increase in power demand due to electric vehicles.

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