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Strategic Planning of Electric Vehicle Charging Station in the Power Distribution Network

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Abstract—

The rapid growth of Electric Vehicles (EVs) necessitates the development of a well-structured and reliable Charging Station (CS) infrastructure to ensure convenient and uninterrupted charging services. Effective CS planning involves the optimal selection of station locations and appropriate charger allocation while maintaining the operational security of the distribution network under increasing EV penetration levels. In this study, a comprehensive planning framework is proposed to support sustainable EV integration by optimizing charging infrastructure deployment. The proposed approach aims to reduce the overall expenditure associated with charging station establishment, operational activities, and network energy losses, thereby creating benefits for charging station investors, distribution network operators, and EV users. To improve charging accessibility and coverage, the distribution network is partitioned into different zones, and charging stations are allocated within each zone based on a zonal planning strategy. Subsequently, the optimal siting and sizing of charging stations are determined using the Harris Hawk Optimization algorithm. In addition, the uncertainty associated with EV charging demand is modelled using probability distribution functions to achieve more realistic planning outcomes. Several case studies are carried out under different planning scenarios to evaluate the effectiveness of the proposed methodology. Comparative analyses are also performed to identify the most suitable planning strategy capable of satisfying the technical and economic requirements of various stakeholders.

Keywords— Distribution Network; Electric Vehicle; Harris Hawk Optimization; Strategic planning; Uncertainty.

I. INTRODUCTION

Electric Vehicles (EVs) have gained significant global attention as a sustainable alternative to conventional transportation systems due to the depletion of fossil fuel resources and increasing environmental concerns. Despite their growing popularity, the large-scale deployment of EVs is still constrained by the insufficient availability of charging infrastructure, which creates inconvenience and uncertainty among EV users. Therefore, the development of an efficient Electric Vehicle Charging Station (EVCS) planning framework has become an essential requirement. Proper EVCS planning involves identifying suitable charging station (CS) locations and determining the optimal number of chargers required at each station to provide reliable and convenient charging services [1]. An effective planning strategy can improve user accessibility, reduce range anxiety, support seamless EV integration into everyday transportation, maximize station utilization, and promote environmentally sustainable mobility.

The placement of charging stations cannot be carried out randomly throughout the electrical distribution network, as improper integration may violate operational constraints and increase the likelihood of network overloading [1]. Hence, charging stations must be strategically located to ensure adequate coverage of the entire service region while maintaining acceptable network operating conditions. In addition, an appropriate spacing between neighbouring charging stations is necessary, and regions with higher charging demand should receive priority during the planning process. Determining the appropriate number of chargers at each station is equally important because excessive charger installation may lead to voltage instability, deterioration in power quality, and increased system power losses [2]. Conversely, insufficient charger availability can result in congestion and longer waiting durations for EV users [3]. For realistic EVCS planning, it is also essential to consider the uncertain and dynamic behaviour of EV charging load.

In earlier works [4], [5], uncertain EV arrival time and travel distance were incorporated into the planning framework; however, battery capacity was not considered. Therefore, to address the uncertainty related to EVs are addressed by using probability density function. Several optimization techniques have been applied in previous literature to determine suitable charging station locations. For example, studies in [4] and [6] utilized the Arithmetic Optimization Algorithm and a hybrid Gray Wolf Optimization–Particle Swarm Optimization approach, respectively. However, the obtained results indicated that charging stations were often concentrated around consecutive buses, leaving large portions of the network insufficiently covered. To ensure high-quality charging services, charging stations should be distributed systematically throughout the planning region rather than clustered in a limited area.

Existing literature has often focused on limited objectives during EVCS planning. Studies in [7], [8] and [9] primarily emphasized minimization of power loss and voltage deviation, whereas works such as [1] and [10] concentrated mainly on charging station-related costs. However, a comprehensive EVCS planning framework should simultaneously address multiple technical and economic factors, including voltage profile improvement, reduction of power losses, minimization of user waiting time, and overall charging infrastructure cost. Such an integrated approach ensures balanced benefits for all major stakeholders, namely charging station owners, Distribution Network Operators (DNOs), and EV users.

In this paper, a comprehensive EVCS planning model is developed to identify the optimal charging station locations and determine the appropriate number of chargers required at each station. The proposed framework aims to minimize charging station installation cost, operational cost, user waiting time, and network energy loss while satisfying operational constraints associated with the power system, EVCS infrastructure, and EV characteristics. The formulated objective function is designed to simultaneously address the interests of charging station investors, DNOs, and EV users. In addition, several case studies are performed and comparatively analyzed to identify the most effective planning strategy. The optimal charger sizing problem is solved using the Harris Hawk Optimization (HHO) algorithm.

The major contributions of the proposed work are summarized as follows:

a) A comprehensive objective function is formulated to minimize charging station cost and energy loss cost while considering operational constraints related to the power system, EVCS, and EV operation.

b) Uncertainties associated with EV operation, including driving distance, battery SOC, battery capacity, are incorporated into the planning framework to achieve more realistic and reliable results.

c) A strategic EVCS planning method is proposed to ensure complete coverage of the planning area while. In addition, the optimal number of chargers is determined using the Harris Hawk Optimization technique.

II. UNCERTAINTY MODELLING

The uncertain parameters considered in the current planning method are EV driving distance before reaching the CS (d), SOC on arrival, battery capacity (Cap_b) and electricity prices (C^{elec}). The SOC and the total charging time (t^{ch}) can be calculated using (1) and (2).

$$SOC = \left(1 - \frac{d}{range\ of\ EV}\right) \qquad (1)$$

$$t^{ch} = \frac{((1-SOC) \times Cap_b)}{(P^{ch} \times \eta_b\ )} \qquad (2)$$

where η_b is the battery efficiency which is taken as 95% in the present problem. In this work, two different types of charging power (P^{ch}) are considered for the analysis i.e., 10 kW AC slow charging and 50 kW DC fast charging. The details of the uncertain variables considered for this planning problem are given below:

1) Driving distance (Miles)

The driving distance of the vehicle is considered to follow the Normal distribution. The mean (μ) and standard deviation (σ) [6] are taken as 60.5 and 20.1 respectively for the current problem. The probability density function of driving distance can be expressed as follows:

$$f(d;\mu,\sigma) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{(d-\mu)^2}{2\sigma^2}} \qquad (3)$$

2) EV battery capacity (kWh)

The battery capacity of the vehicle obeys the Normal distribution. The μ and σ used in the proposed work are 27.5 and 8.9629 respectively and the probability density function is given as follows:

$$f(Cap_b;\mu,\sigma) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{(Cap_b-\mu)^2}{2\sigma^2}} \qquad (4)$$

III. OBJECTIVE FUNCTION AND CONSTRAINTS

A. Objective Function

1) EVCS cost (C_{CS}):

The charging station cost is minimized from the perspective of the charging station owner. This cost component consists of both installation and operational expenditures and is represented as follows:

$$C_{CS} = C_{INS} + C_{OP} \tag{5}$$

a) Installation cost (C_{INS}):

The installation cost depends on various parameters such as land or construction area cost, charger procurement cost, and additional infrastructure-related expenses. The total charging station area includes the space occupied by chargers as well as the parking area required for EVs. The additional cost (C_{other}) includes expenses related to new electrical connections, technician and manpower charges, and station management costs. The installation cost of charging stations is calculated using:

$$C_{INS} = \sum_{st=1}^{N_{st}} R_1 \left[\left\{\sum_{i=1}^{N_{fcs/scs}} \left(A_i^{fcs/scs} \times C_A\right) + \left(N_{i,st}^{fch/sch} \times C_{fch/sch}\right)\right\} + C_{other}\right] \tag{6}$$

Where N_{st} represent the total number of stages. $A_i^{fcs/scs}$ and $A_i^{fch/sch}$ refers to the total sq. ft area required for each fast/slow CS and fast/slow chargers respectively. $A_i^{parking}$ denotes the area required for parking EVs. $N_{fcs/scs}$ represent the number of fast/slow CS and $N_{i,st}^{fch/sch}$ denotes the number of fast/slow chargers required in st^th^ stage in i^th^ CS. C_A and $C_{fch/sch}$ indicates the construction cost per sq. ft area for each CS and cost of fast/slow chargers respectively. *rate* refers to the discount rate which is taken as 0.08 in this paper.

b) Operational cost (C_{OP}):

The operational cost of charging stations depends on the number of chargers installed, charger power ratings, charging duration, and electricity price. The operational expenditure is evaluated for each scenario across all planning stages as follows:

$$C_{OP} = \sum_{st=1}^{N_{st}} \sum_{y=1}^{N_y} \sum_{sc=1}^{N_{sc}} R_1 \left[\left\{\sum_{i=1}^{N_{fcs/scs}} \left(N_{i,st,y,sc}^{fch/sch} \times P^{fch/sch} \times t_{i,st,y,sc}^{fch/sch} \times C_{i,st,y,sc}^{elec}\right)\right\}\right] \times t_{sc} \tag{7}$$

Where N_y , N_{sc} represent total number of planning years, and scenarios respectively and t_{sc} refers to the duration of each scenario. $P^{fch/sch}$ denotes the power rating of fast/slow chargers. $t_{i,st,y,sc}^{fch/sch}$ indicates the charging time for fast/slow chargers of st^{th} stage in y^{th} year at sc^{th} scenario in i^{th} CS. $C_{i,st,y,sc}^{elec}$represent the cost of electricity.

2) Energy loss cost (C_{ENL}):

The energy loss cost is minimized from the viewpoint of the Distribution Network Operators (DNOs). This objective reflects the economic impact of additional network losses caused by EV charging demand. The energy loss cost for all scenarios and planning stages is determined as follows:

$$C_{ENL} = \sum_{st=1}^{N_{st}} \sum_{y=1}^{N_y} \sum_{sc=1}^{N_{sc}} R_1 \left[P_{st,y,sc}^{loss} \times t_{sc} \times C_{i,st,y,sc}^{elec}\right] \tag{8}$$

$P_{st,y,sc}^{loss}$indicates the total power loss of the system and R_1 refers to the conversion factor of installation cost, operational cost, and energy loss cost.

B. Constraints

Equality and inequality constraints are vital aspects of the power system that need to be maintained for satisfactory system operation. For the placement and sizing of EVCS, constraints related to EV and EVCS are given below.

To ensure secure, stable, and efficient operation of the distribution network, several technical constraints are incorporated into the EVCS planning model. A power balance constraint is maintained such that the total generating power is sufficient to meet the combined demand of EV charging stations, existing system load, and network power losses during all planning stages and operating scenarios. In addition, the power flow through each feeder of the distribution network is restricted within its maximum allowable capacity to prevent line overloading and maintain reliable grid operation.

Battery-related constraints are also considered to improve EV battery performance and lifespan. Accordingly, the battery State of Charge (SOC) is maintained within specified minimum and maximum operating limits during the charging process. Furthermore, practical charging infrastructure constraints are imposed by limiting the number of fast and slow chargers installed at each charging station within predefined lower and upper bounds. These constraints help ensure efficient charger utilization, avoid excessive investment, and support reliable EV charging services.

$$P_G = P_L + P_{Loss}$$

$$PF^l < PF_{max}$$

$$V_{min} \le V_{bus} \le V_{max}$$

$$SOC_{min} \le SOC \le SOC_{max}$$

$$N_{ch}^{min} \le N_i^{sch/fch} \le N_{ch}^{max}$$

$$N_{cs} \ge N_{cs}^{min}$$

IV. METHODOLOGY

The proposed methodology aims to determine the optimal location and sizing of EVCSs in the distribution network while considering both technical and economic objectives. The complete planning framework incorporates uncertainty modelling of EV behavior, zonal allocation of charging stations, power flow analysis, and optimization using the HHO algorithm. The methodological framework adopted in this work is illustrated through sequential stages to ensure reliable and effective EVCS planning.

Initially, the electrical distribution network is divided into different geographical zones to guarantee adequate charging accessibility throughout the entire service area. The zonal planning strategy prevents the excessive concentration of charging stations at neighboring buses and ensures balanced distribution of charging infrastructure. The candidate buses for EVCS installation are identified within each zone based on load demand, network topology, and charging accessibility requirements.

Thereafter, the uncertain characteristics of EV charging demand are modelled using probability distribution functions. The driving distance travelled by EVs before arriving at the charging station and the battery capacity of EVs are assumed to follow Normal probability distributions. The uncertainty associated with these variables directly affects the charging demand, charging duration, and State of Charge (SOC) at the charging station. The charging time of EVs is estimated using the battery SOC, battery efficiency, charger power rating, and battery capacity. Two charging technologies are considered in the present work, namely 10 kW AC slow chargers and 50 kW DC fast chargers.

After modelling the EV charging demand, load flow analysis is performed on the distribution network under different charging scenarios. The integration of EV charging load increases the power demand of the system, which may result in voltage deviation and increased power losses. Therefore, power flow constraints and feeder loading limits are incorporated into the planning problem to maintain secure operation of the network.

The optimization problem is formulated as a multi-objective function consisting of charging station installation cost, operational cost, and energy loss cost. The installation cost includes charger procurement cost, land and construction cost, parking infrastructure cost, and additional infrastructure expenditure. The operational cost depends on charging duration, electricity tariff, charger rating, and number of installed chargers. The energy loss cost represents the additional economic burden on the distribution network due to EV charging demand.

To solve the formulated optimization problem, the HHO algorithm is employed. HHO is a nature-inspired population-based optimization technique developed based on the cooperative hunting behavior of Harris hawks. The algorithm possesses strong exploration and exploitation capabilities, enabling it to avoid local optima and obtain high-quality global solutions for complex nonlinear optimization problems.

The optimization process begins with the random initialization of hawk populations representing candidate EVCS planning solutions. Each hawk position corresponds to a possible combination of charging station locations and charger capacities. The fitness value of each solution is evaluated using the proposed objective function while satisfying all operational constraints. During the exploration phase, hawks search different regions of the solution space to identify promising solutions. In the exploitation phase, the hawks gradually converge toward the optimal solution based on the escaping energy behavior of prey. The iterative optimization process continues until the stopping criterion or maximum iteration limit is achieved.

Finally, the optimal charging station locations and charger allocations obtained from the HHO algorithm are comparatively analyzed under different planning scenarios. The performance of the proposed planning methodology is evaluated in terms of charging station cost reduction, energy loss minimization, voltage profile improvement, and charging service accessibility. The detailed methodology adopted in this work is presented in Fig. 1.

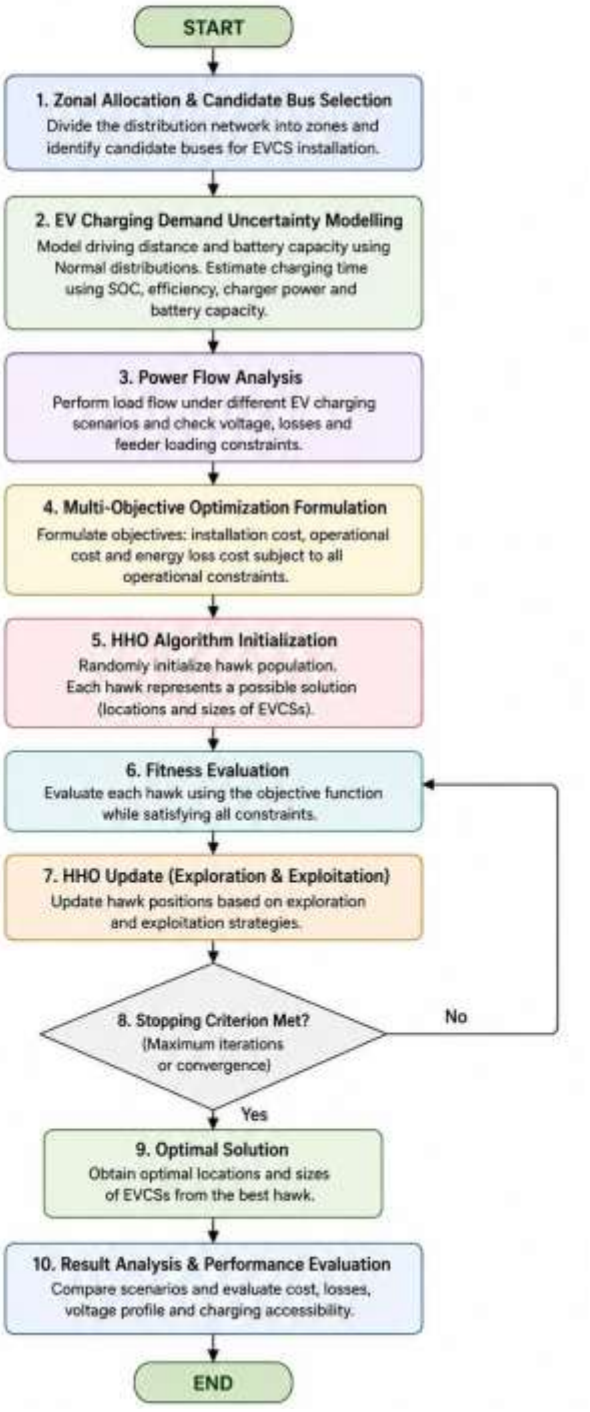

Fig. 1. Flowchart of the proposed methodology

V. RESULT AND DISCUSSION

The proposed EVCS planning methodology was implemented on the test distribution network to determine the optimal locations and sizes of charging stations while satisfying all operational constraints. The HHO algorithm was employed to solve the formulated multi-objective optimization problem considering charging station installation cost, operational cost, and network energy loss cost. The effectiveness of the proposed approach was evaluated under different planning scenarios and charging demand conditions. The 33-bus distribution network is taken as test system. The input parameters are given in Table I.

TABLE I. INPUT PARAMETERS RELATED TO OBJECTIVE FUNCTION

Parameters	Value	Parameters	Value
A^{sch}	0.66 ft²	C_{que}	5.6 $
A^{fch}	5.71 ft²	C_{sch}	815.6 $
$A^{parking}$	1000 ft²	C_{fch}	17,500 $
C_A	27 $	C_{other}	36,783 $

A. Optimal EVCS Allocation Results

The HHO algorithm successfully identified the optimal charging station locations and corresponding charger allocations within the predefined planning zones. The zonal planning strategy ensured that charging stations were distributed throughout the network, thereby avoiding excessive clustering at adjacent buses and improving charging accessibility for EV users. Table II presents the optimal charging station locations along with the number of installed fast and slow chargers obtained from the optimization process.

TABLE II. OPTIMAL EVCS LOCATIONS AND CHARGER ALLOCATIONS

Charging Station	Bus Number	Slow Chargers	Fast Chargers
CS-1	2	4	1
CS-2	11	3	2
CS-3	21	3	1

The obtained results indicate that buses with higher load demand and favourable network characteristics were selected for EVCS installation. Furthermore, the charger allocation reflects the charging demand requirements of individual zones while maintaining acceptable network operating conditions.

B. Impact on Distribution Network Performance

The integration of EV charging load significantly affects the voltage profile and power loss characteristics of the distribution network. Therefore, load flow analysis was performed before and after EVCS installation to evaluate the network performance.

Table III compares the minimum bus voltage and total system power loss under different planning scenarios.

TABLE III. NETWORK PERFORMANCE COMPARISON

Parameter	Base Case	Without Optimization	Proposed HHO
Minimum Voltage (p.u.)	0.9131 p.u.	0.9012	0.9078
Total Power Loss (kW)	200 kW	250 kW	220 kW

The results demonstrate that the proposed planning strategy effectively mitigates the adverse impact of EV charging demand. Compared with the unplanned charging scenario, the optimized EVCS allocation improves the voltage profile and reduces network power losses. This improvement is achieved through strategic placement of charging stations and optimal charger sizing.

C. Cost Analysis

The economic performance of the proposed methodology was evaluated by considering installation cost, operational cost, and energy loss cost. The total planning cost obtained from the optimization process is summarized in Table IV.

TABLE IV. COST COMPONENT ANALYSIS

Cost Component	Cost ($)
Installation Cost	3.456×10^5
Operational Cost	3.321×10^5
Energy Loss Cost	2.106×10^4

It can be observed that the installation cost contributes the largest portion of the total expenditure due to charger procurement, construction requirements, parking facilities, and additional infrastructure costs. However, proper charger allocation significantly reduces operational expenses and network loss costs over the planning horizon.

D. Algorithm Comparison

To further validate the effectiveness of the HHO algorithm in solving the proposed problem, the obtained results are compared with other planning approaches such as Particle Swarm Optimization (PSO), Genetic Algorithm (GA), and Enhanced PSO (EPSO) as shown in Fig. 2. The result indicates that HHO out performs other algorithms in terms of convergence rate.

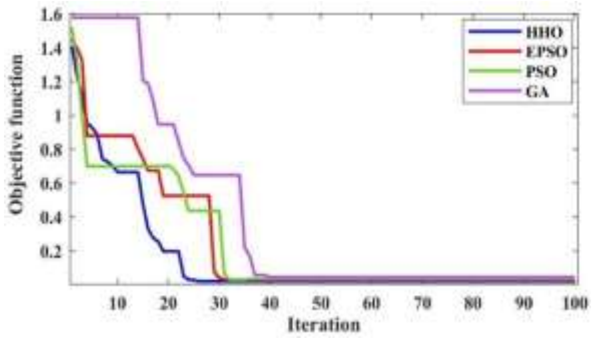

Fig. 2. Convergence characteristics

VI. CONCLUSION

This paper presented a comprehensive planning framework for the optimal siting and sizing of EVCSs in distribution networks. The proposed methodology integrates uncertainty modelling of EV charging demand, zonal allocation of charging stations, power flow analysis, and HHO to address both technical and economic planning objectives. The uncertainties associated with EV driving distance and battery capacity were modelled using probability distribution functions to obtain realistic charging demand estimates. Furthermore, a zonal planning strategy was adopted to ensure balanced charging station distribution and improved charging accessibility across the entire service area.

The optimization problem was formulated to simultaneously minimize charging station installation cost, operational cost, and network energy loss cost while satisfying all operational constraints. Simulation results demonstrated that the proposed HHO-based approach effectively identified optimal charging station locations and charger allocations, resulting in reduced overall planning cost, lower network losses, and improved voltage profile. The comparative analysis further confirmed the capability of the HHO algorithm to provide high-quality solutions for complex EVCS planning problems due to its strong exploration and exploitation characteristics.

Overall, the proposed framework offers a practical and efficient decision-support tool for charging station investors, distribution network operators, and EV users. The methodology can facilitate the sustainable integration of large-scale EV charging infrastructure while maintaining reliable and economical operation of future distribution networks. Future work may focus on incorporating renewable energy sources, battery energy storage systems, vehicle-to-grid (V2G) operation, and dynamic electricity pricing mechanisms to further enhance the effectiveness of EVCS planning.

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