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Optimal Sizing and Locations of Fast Charging Stations for Electric Vehicles Considering Power System Constraints

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ABSTRACT With the increasing adoption of electric vehicles, it becomes crucial to ensure that Fast Charging Stations (FCSs) are strategically located and adequately sized to establish a dependable and accessible charging infrastructure. This study investigates the critical issue of optimizing the size and location of these stations, considering total costs, including investment costs, operation and maintenance costs, cost of power system loss, and power system reliability costs. To address this challenge, Particle Swarm Optimization (PSO), a powerful optimization technique, is employed to identify the optimal sizes and locations of FCSs. The PSO enables the consideration of complex relationships among variables such as Electric Vehicles (EVs) demand, station capacity, and power system limitations. From the perspective of the Transmission System Operator (TSO), the impact of FCSs on power system reliability has been evaluated using an Energy Not Supplied (ENS) index to evaluate power system reliability costs. Simulation results on the 193-bus test system in northeastern Thailand, conducted with Power Factory DIgSILENT software, validate the effectiveness of our proposed model and method. The results demonstrate that our approach not only identifies the optimal placement and size of FCSs with minimal overall costs but also ensures the operational security of the power system. The proposed method can solve the problem rapidly and accurately. Additionally, power system reliability is considered a criterion in the proposed method.

INDEX TERMS electric vehicle charging station; energy not supplied; optimal planning; particle swarm optimization; power system reliability;

I. INTRODUCTION

The global transition towards electric mobility underscores the urgent need for efficient planning of EVs charging infrastructure. In the first half of 2023, the global electric vehicles market experienced a significant increase, with sales rising by 49% to reach an impressive 6.2 million units. This remarkable growth was fueled by a combination of supportive government policies, the easing of supply chain bottlenecks, and a notable increase in consumer demand for electric vehicles. China retained its dominant position, commanding a 55% share of the market, while Europe and the United States also witnessed substantial expansions at rates of 24% and 13%, respectively [1]. This increase underscores a global commitment to cleaner and sustainable transportation alternatives, highlighting the impact of proactive government measures and a growing awareness among consumers. As the world embraces the transition away from traditional fossil-fueled vehicles, the success and sustainability of this shift depend on the development of charging infrastructure. The remarkable surge in electric vehicle (EV) sales underscores the urgent need to address challenges, such as the range anxiety of users for recharging, to effectively accommodate the growing number of EVs on the roads. With governments, industries, and stakeholders actively investing in the expansion of charging infrastructure, the simultaneous development of robust charging infrastructure is essential to facilitate the seamless integration of EVs into mainstream transportation, and ensuring clean energy more accessible. To advance widespread EVs adoption in urban traffic, it is crucial to establish an accessible charging infrastructure capable of recharging EV batteries. Standardized EVs charging levels have been introduced to streamline this process. For example, charging level 1 utilizes a single-phase AC system with a charging power of up to 3 kW, requiring approximately 7 hours to charge a 20 kWh EV battery. Charging level 2 employs a 3-phase AC system with a charging power of up to 24 kW, reducing the charging time to approximately 1 hour for a 20 kWh EV battery. Lastly, charging level 3, widely known as fast charging, employs a DC system that can enable a charge in just 20-30 minutes for a 20 kWh EV battery [2]. Therefore, fast charging is a crucial technology for gaining public acceptance of EVs. FCSs are directly linked to the electrical grid. The station is equipped with devices such as transformers and rectifiers for generating DC currents. Chargers installed in the FCSs use DC currents to charge EV batteries for approximately 20 minutes, making it an efficient electric fuel station conforming to the short-term energy needs of EVs. Concurrent charging at fast stations would impose an extra demand on the grid, leading to increased energy loss [3]. While EVs are widely promoted, their large-scale adoption has the potential to violate the limit of power system operation. Many studies have identified numerous challenges associated with EVs integration, including increased peak demands [4], potential violations of voltage regulatory limits [5], the risk of overloaded infrastructure [6], and reduced power system reliability. These issues can lead to power losses, widespread blackouts, and even equipment damage. To ensure a seamless and sustainable transition towards an EV-dominated future, prioritizing a thorough understanding of how these vehicles impact the power grid upon which they rely is paramount. Moreover, understanding these impacts is crucial for finding the optimal size and location of FCSs, as well as developing effective strategies to mitigate the challenges mentioned above.

The challenge of selecting optimal locations for charging stations has gained significant attention in recent years. In reference [7], a grid partition method was introduced as a means to select the optimal locations of EV charging stations. This technique involved dividing the service area into an electrical grid to simplify the identification of optimal charging station locations. The goal of this approach was to minimize user losses incurred while traveling to charging stations, leading to positive impacts on urban development and grid integration. Similarly, references [8, 9] utilized PSO to optimize the locations and sizes of charging stations. These research works focused on minimizing the overall cost of EV charging infrastructure while ensuring adequate coverage for EV users. The PSO has proven effective in minimizing considered costs, coverage requirements, and constraints imposed by the power grid. Moreover, when compared to other methods such as Genetic Algorithms (GA), PSO exhibits faster convergence, leading to the quicker identification of optimal solutions [10]. According to Reference [11], Particle Swarm Optimization (PSO), Salp-Swarm Algorithm (SSA), and Arithmetic Optimization Algorithm (AOA) were employed to optimize the operation of an EV Fast Charging Station (EVFCS) connected with a renewable energy source and Battery Energy Storage Systems (BESS) for maximizing profit, measured by Net Present Value (NPV). Reference [12] discussed the growing challenge posed by the increasing adoption of EVCS to existing distribution networks. The entrance of EV load raised concerns about system destabilization and reduced voltage quality. To address this issue, a novel approach leveraging PSO was proposed. This approach aimed to identify optimal EVCS locations within the IEEE 33-bus radial distribution system. In reference [13], the proposed method optimized the placement of EV charging stations in Ireland. This approach, based on cost modeling and GA, aimed to minimize a social cost model that considered both economic and environmental factors. Similarly, in reference [14], a genetic algorithm (GA) approach based on graph theory was utilized to strategically place Electric Vehicle Charging Stations (EVCS) in urban areas. This involved modeling the urban landscape as a weighted graph using reference nodes and employing the Dijkstra method to determine minimum-cost paths. In references [15], an Enhanced Heuristic Descent Gradient (EHDG) algorithm with a Voronoi diagram approach was proposed for placing electric bus charging stations to minimize costs and consumption. Its effectiveness was demonstrated through a real-world case study in Toronto. Reference [16] took a different perspective by integrating the planning of EV charging stations into distribution systems, with a focus on optimizing the size and location of EV charging stations to minimize the impact on distribution network operation. References [17, 18] addressed the planning of both slow and fast charging facilities in urban areas, aiming to balance the need for convenience and cost-effective charging options to provide diverse user preferences and charging time requirements. In reference [19], the EVCS placement adopted a holistic approach which integrated a radial distribution network with a road network and assigned weightage based on charging demand from various areas. The objectives included minimizing energy loss, voltage deviation, and land cost, while prioritizing maximizing EV service and minimizing establishment costs. A three-zone division strategy optimized EVCS distribution, and the study addressed uncertainties related to EVs using the 2m Point Estimation method. The study applied optimization techniques such as Differential Evolution (DE) and Harris Hawks Optimization (HHO) to solve the problem. Most existing research works focused on optimizing the location and size of charging stations using various methods and strategies; however, they often overlook the crucial aspect of power system reliability,

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particularly when dealing with a substantial expansion of charging station infrastructure. The amount of power lost in an uneven electrical distribution system (unbalanced radial distribution system) was investigated in reference [20] as a potential guide for the placement of charging stations for EVCS. An optimization problem was formulated to achieve this and solved using a technique called PSO. Similarly, in reference [21], A two-way power flow can be provided by EVCSs, thereby balancing the demand between electric vehicles and the grid. This research proposes a strategy for achieving optimal placement of these renewable-powered EVCSs within large distribution networks. The focus of this strategy is to achieve power balance, improved voltage stability, and minimized power loss. Reference [22], several factors are considered in this study to identify optimal locations for EVCS placement, with a focus on minimizing power loss. These factors include the construction cost of the stations, the economic impact of power loss, and the cost associated with voltage fluctuations.

To achieve optimal placement considering all these aspects, a sophisticated method known as the balanced mayfly algorithm was employed. In reference [23], a balance between driver convenience and cost minimization for EVCS is investigated in this study. This is achieved by considering factors such as construction costs, power loss reduction, traffic flow patterns, and minimized driver waiting times. To account for the unpredictable nature of daily driving patterns, a special technique is employed. Finally, by clustering locations with high EV presence, the optimal placement of EVCSs throughout the day is determined.

Consequently, this study focuses on minimizing the total cost, encompassing investment costs, operational and maintenance costs, electrical grid loss costs, and electric power system reliability costs. EVs demand is considered within the service area, as well as electric power system constraints such as transformer capacity, voltage limits and transmission line limits.

TABLE 1. Comparison of optimization objective and electrical grid aspect in planning EVCS siting and sizing.

Paper	Problem	Main optimization goal	Electrical grid aspect
S. Ge et al. (2011) [7]	Location and sizing	Minimize the distance (or the deviation) to a charging station	No
Z. -f. Liu et al. (2012) [8]	Location and sizing	Minimize the social cost of charging stations	No
Hou et al. (2021) [9]	Location and sizing	Minimize the social cost of charging stations	No
A. Awasthi et al. (2016) [10]	Location and sizing	Minimize the social cost of charging stations	Yes (distribution system)
Antarasee et al. (2023) [11]	Sizing (capacity)	Maximizing profit, measured by Net Present Value (NPV)	No
D. Srinivas et al. (2022) [12]	Location and sizing	Maximize the amount of energy charged	Yes (distribution system)
Zhou et al. (2022) [13]	Location	Minimize the social cost of charging stations	No
T. G. Altundogan et al. (2021) [14]	Location	Minimize the distance (or the deviation) to a charging station	No
Othman et al. (2020) [15]	Location	Minimize the energy consumption and operating cost	No
Z. Liu et al. (2013) [16]	Location and sizing	Minimize the social cost of charging stations	Yes (distribution system)
Sadeghi-Barzani et al. (2014) [17]	Location and sizing	Minimize the social cost of charging stations	Yes (distribution system)
L. Jia et al. (2014) [18]	Location and sizing	Minimize the social cost of charging stations	No
Pal et al. (2021) [19]	Location and sizing	Minimize the social cost of charging stations	Yes (distribution system)
Reddy et al. (2020) [20]	Location and sizing	Minimize power losses	Yes (distribution system)
Datta et al. (2021) [21]	Location and sizing	Minimize power losses	Yes (distribution system)
Chen et al. (2021) [22]	Location and sizing	Minimize the social cost of charging stations	Yes (distribution system)
Tadayon-Roody et al. (2021) [23]	Location and sizing	Minimize the social cost of charging stations	Yes (distribution system)

Additionally, both highways and urban roads are considered to identify optimal locations for FCSs. This paper provides a thorough examination of the problem characteristics, establishes a necessary condition for deploying a FCSs, and derives the upper and lower bounds for the number of chargers required at each station. The main contributions of this paper can be summarized as follows.

(1) This study proposes an approach for optimizing the size and location of FCSs using PSO, considering power system reliability as one of the parameters in the objective function, leading to a more balanced, secure, and sustainable deployment of FCSs, which is essential for the long-term success of electric vehicle infrastructure.

(2) This research makes a substantial contribution by tapping into authentic datasets derived from Thailand's tangible electrical system, highways, and urban roads. The deliberate use of real-world data facilitates a thorough exploration of practical constraints inherent in both the power and traffic systems. By directly engaging with actual data, our study deepens the comprehension of these intricacies, thereby amplifying the significance and applicability of our findings within real-world contexts. The effectiveness of the proposed model and method is rigorously validated through the use of Power Factory DIgSILENT software.

The paper's structure is presented as follows. Section II presents the problem formulation. The optimization model and the flowchart of the proposed method for addressing the issue are explained in Section III. Section IV presents the results and discussions derived from the studies. Finally, Section V provides a conclusion of this work.

II. Problem Formulation

In this section, a systematic evaluation of the overall cost has been proposed and a comprehensive cost model encompassing various cost components has been developed. The construction of this model can be divided into two main phases: the initial phase involved constructing the complete cost model, and the subsequent phase focused on optimizing the quantitative aspects. A model for evaluating the total cost, including investment costs, operational and maintenance costs, electrical grid loss costs, and electric power system reliability costs, has been established. Furthermore, specific constraints have been introduced into the analysis, resulting in the development of a quantitative model capable of appropriately evaluating the total cost. This methodology is based on the optimized total cost model and its associated constraint conditions.

A. Objective function

The objective function for minimizing the total cost associated with the planning of FCSs considers investment costs, operation and maintenance costs, electrical grid loss costs, and electric power system reliability costs. It is presented as the following equation:

$$\min F = C_{Inv} + C_{O\&M} + C_{Gridloss} + C_{Relia} + penalty \tag{1}$$

where C_{Inv} is the annual investment cost of the FCSs ($). $C_{O\&M}$ is the annual operation and maintenance cost of the FCSs ($). $C_{Gridloss}$ is the annual electrical grid loss cost ($). C_{Relia} is the annual electric power system reliability cost ($). *penalty* is the additional cost when constraints are violated ($).

1) INVESTMENT COST

The annual investment cost is the primary expense in the planning phase for installing charging stations. It encompasses the cost of equipment to enhance charging stations, the cost of chargers, and necessary facilities [29], which can be computed using the following equation:

$$C_{Inv} = \sum_{i=1}^{N_c} \beta \left(N_i C_{CH} + N_i C_G P_{CH} + C_{I0} \right) \tag{2}$$

where C_{CH} is the investment expenditures for the charging facilities comprise the investment cost per spot for FCSs ($). C_G is the connector development cost ($/kW). C_{I0} is the other investment costs for FCSs ($), such as expenses for construction and road enhancements. P_{CH} is the rated charging power of a fast charging spot (kW). N_C is the total number of FCSs. N_i is the number of chargers in FCS i, where i is the index of FCS candidates.

2) OPERATION AND MAINTENANCE COST

The annual operation and maintenance cost, involving expenses such as routine maintenance and equipment repair, ensuring the selection of stations with efficient operation [18], which can be accomplished using the following equation:

$$C_{O\&M} = \beta \left(\sum_{i=1}^{N_c} C_P N_i P_{CH} \right) \tag{3}$$

where C_P is the operation cost of charging stations of unit capacity ($/kVA).

The annual investment cost and annual operation and maintenance cost are converted from the future cost to the present cost using the asset recovery factor in (4).

$$\beta = \frac{\alpha (1+\alpha)^n}{(1+\alpha)^n - 1} \tag{4}$$

where β is the capital recovery factor. α is the discount rate. n is the planned operational service life of the FCS (years).

3) ELECTRICAL GRID LOSS COST

The grid loss is defined as the total power loss when the FCSs are used. The charging load of EVs is transferred to the electrical grid through high-voltage substations, leading to an increase in electrical grid losses. Because electrical grids have a loop architecture, these losses display non-linear correlations with the load. The electrical grid loss cost can be calculated as follows:

$$C_{Gridloss} = (\Delta Grid\ \ Loss)\ C_{Loss} \tag{5}$$

where $\Delta Grid\ Loss$ is the difference in electrical grid loss before and after the installation of FCSs (kW). C_{Loss} is the operation loss cost of the FCS ($/kW) which can be explained as follows:

$$C_{Loss} = EP\, T_{day}^{f}\ (1\text{-}\gamma_f) \tag{6}$$

where EP is the electricity price ($/kWh). T_{day}^{f} is the daily available charging time of chargers in FCS (hr.). γ_f is the vacancy rate of chargers in FCS.

4) ELECTRIC POWER SYSTEM RELIABILITY COST

The electric power system reliability cost, which involves maintaining power grid reliability, can be accomplished using the equation (7). Including reliability costs in the model aligns the optimization process with TSO objectives, ensuring that the resulting charging infrastructure solutions contribute to a stable and reliable power system:

$$C_{Relia} = (\Delta ENS)\ IC \tag{7}$$

where ΔENS is the difference in Energy Not Supplied (ENS) value before and after the installation of FCSs (kWh). IC the average interruption cost ($/kWh).

Failures in essential electrical components, such as transformers and power lines, can lead to interruptions in the supply of electricity to customers, as indicated in the equation below [24].

$$U_{tx} = \lambda_{tx} r_{tx}\ ,\ tx = 1, 2, 3 \ldots, N_{tx} \tag{8}$$

where U_{tx} is the average annual outage time (hr./year) of transformers tx, where tx is the transformers index. λ_{tx} is the transformer failure rate (failure/year). r_{tx} is the average transformer outage time (hr.). N_{tx} is the number of transformers.

ENS is a crucial system energy index, representing the total amount of energy that remains undelivered to the system loads [30].

$$ENS = \sum_{tx=1}^{N_{tx}} L_{a(tx)} U_{tx} \tag{9}$$

where $L_{a(tx)}$ is the average load connected to transformer tx (kw).

B. Constraints

In this paper, two distinct parts of constraints have been considered. The first part encompasses FCSs constraints, such as the demand for EVs, the quantity of FCSs, and the number of chargers. These factors play a crucial role in determining the overall feasibility and effectiveness of FCS placement and sizing. The second part focuses on electric power system constraints, including power flow equations, voltage limitations, and transformer capacity. These constraints ensure the operation of the power grid when integrating a significant number of FCSs, preventing potential overloading or disruptions. These constraints into two distinct categories have been instrumental in providing a comprehensive and well-rounded analysis.

1. FAST CHARGING STATION CONSTRAINTS

The construction of FCSs is designed to fulfill user charging demands. Therefore, the capacity of each FCS should be sufficient to accommodate all the arriving electric vehicles as presented below [18].

$$D_k \le \sum_{i=1}^{N_C} x_{ik} N_i P_{CH} T_{day}^{f} (1-\gamma_f)\ ,\ \mathrm{k} = 1, 2, 3 \ldots, N_D \tag{10}$$

where D_k is the charging demand in area k, where k is the index of areas (provinces). x_{ik} is the decision variable of FCS i in area k. When demand in area k is charged in FCS i, $x_{ik} = 1$; otherwise, $x_{ik} = 0$. N_D is the number of areas (provinces).

In areas with demand, it is necessary to have at least one FCS, as presented in the below equation.

$$\sum_{g=1}^{N_c} N_g > 0\ , g \in A_D \tag{11}$$

where N_g is the number of FCSs in area with demand. g is the index of area (provinces) with demand, A_D is the set of areas (provinces) with demand.

The upper and lower bounds of the capacity of each FCS which are depended on the number of chargers, as shown below.

$$N_{i_{\min}} \le N_i \le N_{i_{\max}} \tag{12}$$

where $N_{i_{\min}}$ and $N_{i_{\max}}$ are the minimum and maximum number of chargers in FCS i, respectively.

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2. ELECTRIC POWER SYSTEM CONSTRAINTS

The active power and reactive power at bus are presented below [25].

$$P_h = \sum_{m=1}^{N} |V_h||V_m|(G_{hm}\cos\theta_{hm} - B_{hm}\sin\theta_{hm}) \tag{13}$$

$$Q_h = \sum_{m=1}^{N} |V_h||V_m|(G_{hm}\sin\theta_{hm} - B_{hm}\cos\theta_{hm}) \tag{14}$$

where P_h is active power at bus h (MW). Q_h is reactive power at bus h (MVAR), where h and m are bus indexes. N is the number of buses. G_{hm} is conductance between bus h and bus m (Siemens: S). B_{hm} is susceptance between bus h and bus m (Siemens: S). and θ_{hm} is phase angle difference between voltages at bus h and bus m (radians).

The lower and upper voltage limits at each bus.

$$0.95pu. \le V_{bus,h} \le 1.05pu.\ , h = 1,2,3..., N_h \tag{15}$$

where $V_{bus,h}$ is the voltage level at bus h ($pu.$). h is the buses index. N_h is the number of buses.

The high voltage transformer capacity limits.

$$S_{TRtx} \le S_{TRtx}^{rated}\ ,\ tx = 1,2,3..., N_{tx} \tag{16}$$

where S_{TRtx} is the apparent power of high voltage transformer tx (MVA). S_{TRtx}^{rated} is the rated capacity of high voltage transformer tx (MVA).

The transmission line capacity limits.

$$S_{Lnx} \le S_{Lnx}^{rated}\ , nx = 1,2,3..., N_{nx} \tag{17}$$

where S_{Lnx} is the apparent power flow of transmission line nx (MVA). S_{Lnx}^{rated} is the rated capacity of transmission line nx (MVA). nx is the transmission lines index. N_{nx} is the number of transmission lines.

III. Particle Swarm Optimization for Solving Optimal Size and Locations of FCSs

PSO is a global search optimization technique inspired by the social behavior of bird flocks or fish schools. This approach emulates the motion of a particle swarm traversing a search space, where each particle serves as a potential solution to an optimization challenge. These particles dynamically adapt their positions, drawing from their own experiences and the best solutions known to the entire swarm. The core objective of PSO is to iteratively update particle positions, promoting a balanced exploration-exploitation strategy in the quest for the optimal solution. One of its key advantages is its simplicity and efficiency, making it well-suited for a wide range of optimization problems, including function optimization, parameter tuning, and even machine learning model hyperparameter optimization. PSO is known for its ability to quickly converge to near-optimal solutions and its ease of implementation. In Fig. 1, the process of solving optimal size and locations of FCS is presented.

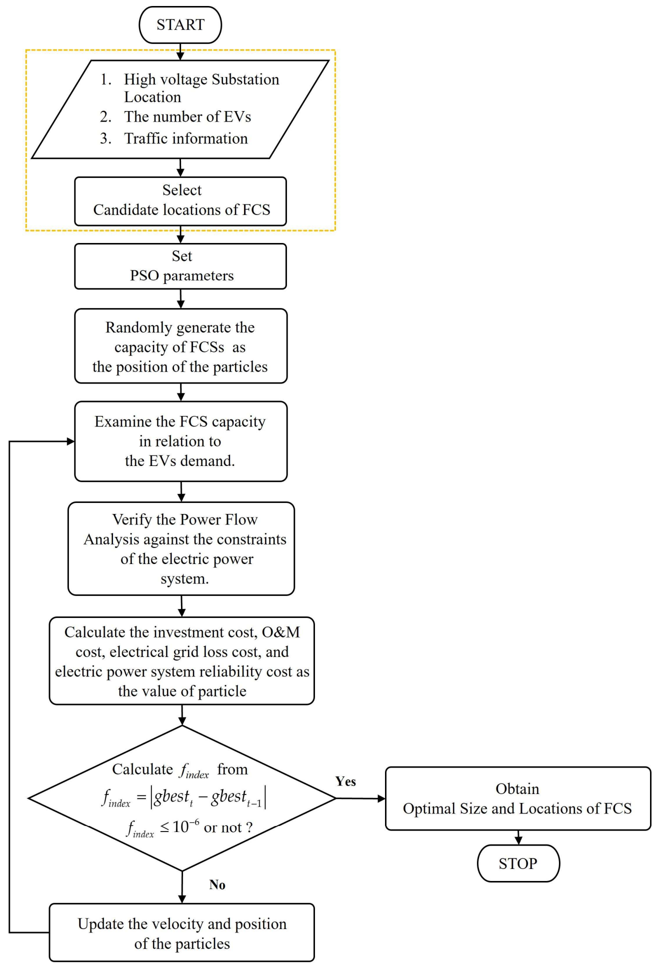

FIGURE 1. Flowchart of the proposed methodology.

The PSO algorithm for optimal planning of fast charging stations is implemented in Python, a widely used, high-level, general-purpose programming language. Power Factory Dig-SILENT provides a Python module you can use to interact with its software. This module, essentially an API (Application Programming Interface) bridge, allows your Python scripts to access and manipulate the vast amount of data stored within Power Factory Dig-SILENT.

The problem-solving process is principally categorized into the following steps:

Step 1: The input data consist of the locations of high voltage substations, the number of EV ownership, and traffic information in the Northeastern Region of Thailand. These data are utilized to determine potential locations for FCSs, specifically for the selection of candidate FCS locations.

Step 2: Set PSO parameters consisting of the number of particle swarm (N), uniform random numbers (r_1, r_2), acceleration constants (C_1, C_2) and the inertia weight (w), as indicated in Table 2.

TABLE 2. PSO parameters.

Parameter	Value
the number of particle swarm *(N)*	500
uniform random numbers *(r1, r2)*	0 and 1
acceleration constants *(C1, C2)*	0.8010
the inertia weight (*w*)	1.6609

Step 3: Randomly generate the capacity of FCSs within the planning area and utilize these station capacities as the positions of particles.

Step 4: Examine the restrictions of the capacity of FCSs in connection with the EVs demand, as detailed in (10).

Step 5: Run power flow analysis in accordance with the electric power system constraints, as described in (13)-(17).

Step 6: Calculate the investment cost, the operation and maintenance cost of FCSs, the electrical grid losses cost, and the electric power system reliability cost according to (2)-(9). Then use (1) to calculate the total costs associated with the planned FCSs and use these values as the particle. Additionally, employ a penalty function to manage particles that do not adhere to the constraints. After that, identify both the personal optimal value ($pbest_{q,t}$) and the global optimal value ($gbest_t$), where q is the index of particles.

Step 7: Determine a termination index in (18), if the global optimal value ($gbest_t$) repeats fifteen times within the criterion $f_{index} \leq 10^{-6}$, proceed to step 9; otherwise, continue to step 8.

$$f_{index} = \left|gbest_t - gbest_{t-1}\right| \tag{18}$$

where f_{index} represents the change in the global optimal value after each iteration of the PSO process.

Step 8: Update the velocity and position of the particles using (19) and (20), respectively. Then, return to step 4 and increase the number of iterations by one.

$$v_{q,t} = wv_{q,t-1} + C_1 r_1 \left(pbest_{q,t-1} - x_{q,t-1}\right) + C_2 r_2 \left(gbest_{q-1} - x_{q,t-1}\right) \tag{19}$$

$$x_{q,t} = x_{q,t-1} + v_{q,t} \tag{20}$$

where $v_{q,t}$ is the velocity of the particle q in iteration t. $x_{q,t}$ is the position of the particle q in iteration t.

Step 9: Obtain the optimal locations for each charging station along with their corresponding service areas, the associated planning costs, and the number of chargers in each station.

IV. Numerical Results and Discussion

In this section, the simulation is employed to assess the compatibility of potential FCS locations with the existing infrastructure, taking into account the perspective of the TSO. Moreover, the presentation of simulation results obtained through the optimization algorithm known as PSO is provided. For this research work, the Power Factory DigSILENT program is utilized. The computational resources employed consist of an Intel(R) Core (TM) i7-12700 CPU @ 2.10 GHz with 64 GB RAM. Furthermore, the investigation of the impact of electrical grid reliability on the optimal placement and sizing of FCSs is undertaken. This analysis takes into consideration the potential implications for customer satisfaction and economic losses.

A. Study case description

The proposed method has been implemented in the northeastern region of Thailand; it covers an area of more than 168,855 km^2. The northeastern region has 20 areas (provinces). This study selects 10 areas (provinces) in the northeastern region and assesses potential FCSs locations using data from Electricity Generating Authority of Thailand (EGAT) high-voltage substations.

In terms of transportation, the northeastern region is primarily connected by a network of highways and urban roads, making it highly accessible for sub-areas. This extensive road network is conducive to the widespread adoption of electric vehicles as a means of transportation, although it also necessitates careful planning for the placement of charging stations. As a result, the simulation results concerning the optimal arrangement of charging stations in this region are highly relevant for countries characterized by developed economies and high rates of car ownership.

In this paper, the electrical transmission systems in the study area encompass voltage levels of 500kV, 230kV, 115kV, and 22kV. This system is composed of 193 buses, 218 lines, and 143 transformers.

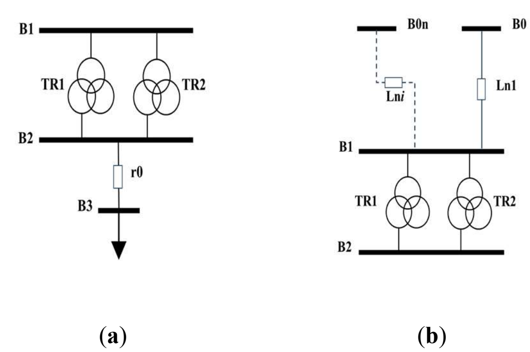

FIGURE 2. (a) Single line diagram for high voltage substation connection to fast charging station. (b) Single line diagram of PQ bus connections.

Fig. 2 (a). illustrates the electrical line diagram depicting the connection of FCSs to a high-voltage substation. B1 and B2 are denoted as the high-voltage 115kV and medium-voltage 22kV bus bars within the high voltage substation, respectively.

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The high voltage substation includes two transformers. B3 represents the low-voltage bus bar of the FCSs, while r0 is an overhead line to the FCSs bus bar. Fig. 2 (b). illustrates the single-line diagram of a B1 PQ bus, where B1 is connected to other high-voltage substations (B0) by a transmission line (Ln1) and connected to other high-voltage substations (B0n) by a transmission line (Ln*i*).

According to data from 2018 to 2022, electric vehicle ownership in Thailand's northeastern regions accounted for 5% of the country's total [22]. Additionally, the anticipated electric vehicle ownership in Thailand for 2030 is mentioned [23]. This data has been utilized to project the ownership of electric vehicles in the northeastern region for the year 2030, as shown in Table 3. In the first ten months of 2022 (January to October), Thailand confronted a significant increase in electric vehicle registrations. The top 10 best-selling EV models have an average battery capacity of 57.85 kWh [29].

TABLE 3. Top 10 areas (provinces) of EV possession in the northeastern region of Thailand in 2030.

Area (Province)	Anticipated number of EV in 2030	EV. Share (%)
Khon Kaen	9,399	25.06
Nakhon Ratchasima	6,584	17.56
Udon Thani	5,248	13.99
Ubon Ratchatani	4,008	10.69
Surin	1,574	4.20
Sakon Nakhon	1,479	3.94
Chaiyaphum	1,336	3.56
Buri Ram	1,145	3.05
Roi Et	1,097	2.93
Loei	1,097	2.93

TABLE 4. Parameters in objective functions and constraints.

Parameter	Value	Unit
Investment cost per spot, C_{CH}	40,550 [24]	$
Connector development cost, C_G	208.33 [17]	$/kW
Other investment costs, C_{I0}	37,840 [24]	$
Operation cost of charging stations of unit capacity, C_P	5 [18]	$/kVA
Rated charging power of a fast charging spot, P_{CH}	100	kW
Electricity price, EP	0.108 [a]	$/kWh
Average interruption cost, IC	0.579 [26,27]	$/kWh
Daily available charging time of chargers in FCS, T^{f}_{day}	18 [18]	hr.
Vacancy rate of chargers in FCS, γ_f	0.2 [18]	
Planned operational service life of the FCS, n	10 [25]	years
Discount rate, α	0.08 [25]	

[a] Average electricity price in Thailand

The details of the study parameter settings, including the values of all parameters used in the objective function and constraints, are reported in Table 4.

Twenty EGAT high-voltage substations have been identified as potential locations for installing FCSs. These stations are strategically chosen to be in areas with high EV ownership rates. Fig. 3 shows the distribution of electric vehicle ownership in the northeastern region for the year 2030. This helped identify comprehensive candidate locations for FCSs along major transportation routes.

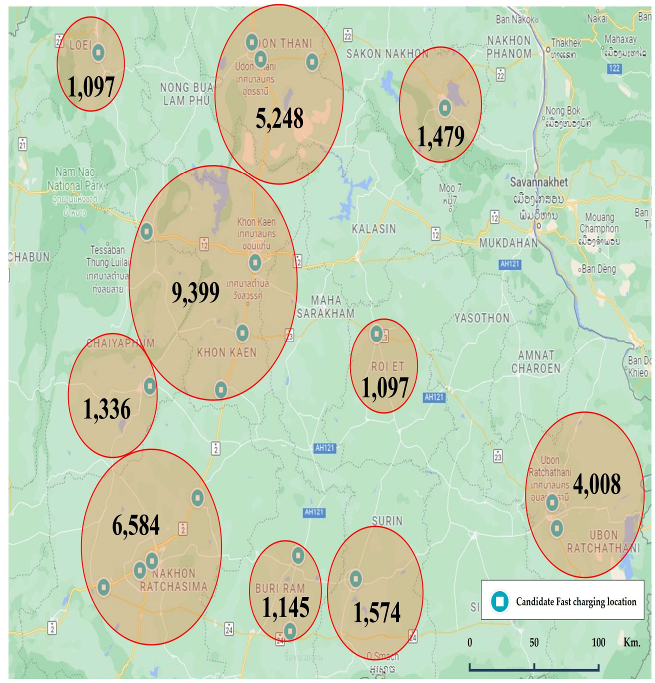

FIGURE 3. Candidate location of fast charging stations and the number of electric vehicles in the northeastern region of Thailand.

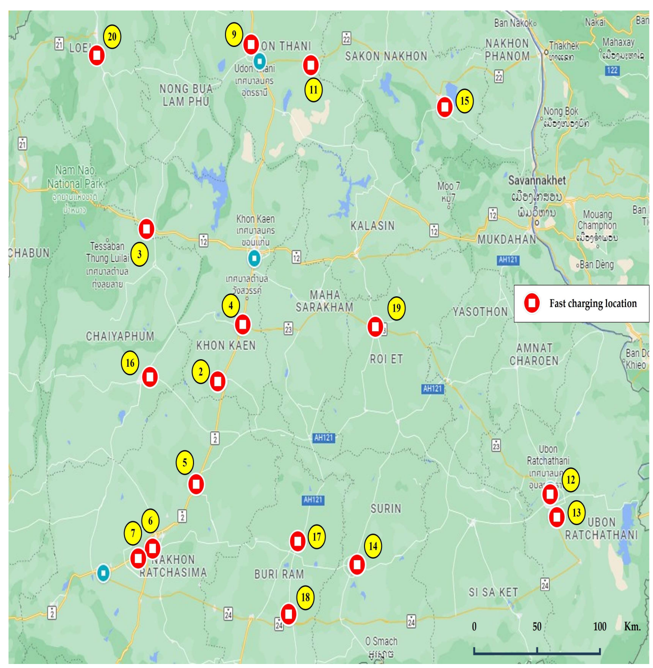

FIGURE 4. Fast charging station's locations in each service area (province).

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B. Simulation Result

The minimum annual total cost of the FCSs is 12.5777 M$. Table 5 presents information about the total cost, composed of investment cost, operation and maintenance cost, and electric power system reliability costs, as well as the number of chargers and the FCS capacity in each station. Additionally, the minimum electrical grid loss cost after FCSs installation is 0.0099 M$. The study identified a need for 1,342 chargers across the northeastern region, with all locations requiring installation. It is noteworthy that each FCS incurs varying investment costs, operation and maintenance costs, and power system reliability costs. Importantly, the investment cost and operation and maintenance costs play a substantial role in determining the total cost, and these expenses are directly proportional to the number of chargers.

The number of chargers is dependent on the quantity of EVs in the FCS's service area, indicating that stations catering to a larger number of EVs will experience higher investment and operation and maintenance costs. The simulation results are depicted in Fig. 4, and the iterative process of the PSO is illustrated in Fig. 5.

The efficacy of metaheuristic techniques, such as PSO, lies in their ability to generate optimal solutions within a reasonable time frame, eliminating the need for computationally intractable exhaustive searches. The PSO algorithm demonstrates remarkable efficiency in determining the optimal capacity and location of FCSs in the northeastern region, In the third run of the PSO algorithm, convergence to the optimal solution was achieved within 252 iterations, as illustrated in Fig. 5.

TABLE 5. Optimal planning result of fast charging stations.

Area (Province)	Candidate Locations	Number of chargers	Investment Cost (M$)	Operation and Maintenance Cost (M$)	Electrical grid losses cost (M$)	Electric power system Reliability cost (M$)	Total Cost (M$)	Total Capacity (MW)
Khon Kaen	1	-	-	-	-	-	-	-
	2	165	1.5150	0.0123	0.0006	0.0118	1.5397	16.50
	3	94	0.8655	0.0070	0.0005	0.0067	0.8797	9.40
	4	119	1.0942	0.0089	0.0008	0.0085	1.1124	11.90
Nakhon Ratchasima	5	120	1.1033	0.0089	0.0010	0.0086	1.1218	12.00
	6	127	1.1674	0.0095	0.0003	0.0091	1.1863	12.70
	7	18	0.1703	0.0013	0.0000	0.0013	0.1729	1.80
	8	-	-	-	-	-	-	-
Udon Thani	9	52	0.4813	0.0039	0.0007	0.0037	0.4896	5.20
	10	-	-	-	-	-	-	-
	11	166	1.5241	0.0124	0.0019	0.0119	1.5503	16.60
Ubon Ratchatani	12	67	0.6185	0.0050	0.0004	0.0048	0.6287	6.70
	13	94	0.8655	0.0070	0.0004	0.0067	0.8796	9.40
Surin	14	72	0.6643	0.0054	0.0008	0.0051	0.6756	7.20
Sakon Nakhon	15	60	0.5545	0.0045	0.0004	0.0043	0.5637	6.00
Chaiyaphum	16	54	0.4996	0.0040	0.0003	0.0039	0.5078	5.40
Buri Ram	17	37	0.3441	0.0028	0.0005	0.0026	0.35	3.70
	18	9	0.0880	0.0007	0.0002	0.0006	0.0895	0.90
Roi Et	19	44	0.4081	0.0033	0.0002	0.0031	0.4147	4.40
Loei	20	44	0.4081	0.0033	0.0009	0.0031	0.4154	4.40
Total		1,342	12.3718	0.1002	0.0099	0.0958	12.5777	134.2

*M$ = Million United States Dollars.

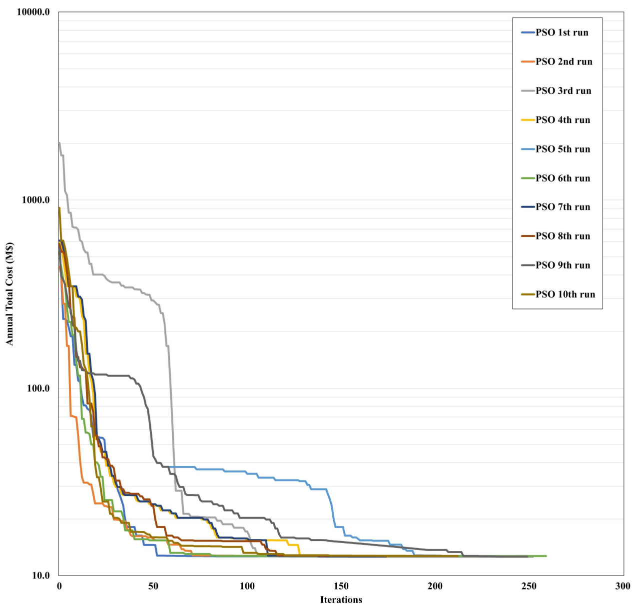

FIGURE 5. The optimization process (10 Executions).

C. Electric power system reliability impact study

Additionally crucial is the influence of electrical grid reliability on the optimal placement and sizing of FCSs. Table 7 serves as the input data for evaluating reliability, containing information used to calculate component failure rates and average outage time, as presented in equation (8).

TABLE 7. Reliability study parameters.

		Value	Unit
Transformer	Failure rate, λ_{tx}	0.1395 [28]	Failure/year
	Repair time, r_{tx}	8.84 [28]	hr.

The ENS index serves as a critical reliability, directly impacting customer satisfaction and economic losses. A dependable power system, characterized by low ENS values, guarantees consumers consistent access to electricity when they need it most. The costs associated with ENS can be substantial for both customers and utilities. Customers may incur economic losses due to power outages, including lost productivity, spoiled inventory, and general inconvenience. Utilities, on the other hand, may bear the costs associated with power restoration, equipment repairs, and compensation for customer outages. While the electric power system reliability cost is a relatively small component of the total cost, as illustrated in Table 8. The installation of additional charging stations has implications for the electric power system. It leads to a significant increase in electrical demand during peak demand periods, highlighting the considerable for the electric power system, customer satisfaction, and economic losses.

TABLE 8. Reliability-included optimization results.

Area (Province)	Candidate Stations	$L_{a(i)}$ (MW)	ΔENS (MWh)	Electric power system reliability cost (M$)
Khon Kaen	2,3,4	37.80	46.614	0.0270
Nakhon Ratchasima	5,6,7	26.50	32.679	0.0190
Udon Thani	9,11	21.80	26.883	0.0156
Ubon Ratchatani	12,13	16.10	19.854	0.0115
Surin	14	7.20	8.879	0.0051
Sakon Nakhon	15	6.00	7.399	0.0043
Chaiyaphum	16	5.40	6.659	0.0039
Buri Ram	17,18	4.60	5.673	0.0032
Roi Et	19	4.40	5.426	0.0031
Loei	20	4.40	5.426	0.0031
Total		134.2	165.492	0.0958

D. Sensitivity analysis

As the number of EVs is forecast to surge by 20%, four times the number previously anticipated for 2030 in Northeastern Thailand, FCS planning is inevitably impacted by the increase in investment and operation and maintenance costs.

Based on the data in Table 6, a significant increase in the anticipated number of EVs in the northeastern region for 2030 has been identified. This necessitates a substantial increase in the number of chargers installed per station, resulting in a 20% rise in investment and operation and maintenance costs. The number of FCSs, electrical grid losses cost, and electric power system reliability cost, however, remain relatively unchanged.

Furthermore, to address the continuous rise in EVs within the northeastern region, adjustments will be made to the number of chargers per station in order to meet the demand for additional charging. This trend of installing a number of chargers that meets the demand for supplementary power is likely to be continued in future FCS construction.

Fig. 6 illustrates that the PSO algorithm achieves remarkable efficiency in identifying the optimal capacity and location of FCSs in the northeastern region. In the fifth run of the PSO algorithm, convergence to the optimal solution is achieved within 219 iterations.

TABLE 6. The number of EVs is expected to surge by 20% above the number anticipated in 2030.

Area (Province)	Anticipated number of EV in 2030	20% above the number anticipated in 2030.
Khon Kaen	9,399	11,279
Nakhon Ratchasima	6,584	7,900
Udon Thani	5,248	6,298
Ubon Ratchatani	4,008	4,810
Surin	1,574	1,889
Sakon Nakhon	1,479	1,775
Chaiyaphum	1,336	1,603
Buri Ram	1,145	1,374
Roi Et	1,097	1,316
Loei	1,097	1,316

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TABLE 9. Optimal planning result of fast charging stations after the number of EVs is expected to surge by 20% above the number anticipated in 2030.

Area (Province)	Candidate Locations	Number of chargers	Investment Cost (M$)	Operation and Maintenance Cost (M$)	Electrical grid losses cost (M$)	Electric power system Reliability cost (M$)	Total Cost (M$)	Total Capacity (MW)
Khon Kaen	1	-	-	-	-	-	-	-
	2	222	2.0364	0.0165	0.0009	0.0159	2.0697	22.2
	3	82	0.7557	0.0061	0.0005	0.0059	0.7681	8.2
	4	150	1.3778	0.0112	0.0011	0.0107	1.4007	15
Nakhon Ratchasima	5	-	-	-	-	-	-	-
	6	65	0.6002	0.0048	0.0002	0.0046	0.6099	6.5
	7	180	1.6522	0.0134	0.0003	0.0129	1.6787	18
	8	73	0.6734	0.0054	0.0000	0.0052	0.6841	7.3
Udon Thani	9	56	0.5179	0.0042	0.0007	0.0040	0.5268	5.6
	10	61	0.5636	0.0045	0.0005	0.0044	0.5730	6.1
	11	145	1.3320	0.0108	0.0017	0.0104	1.3548	14.5
Ubon Ratchatani	12	67	0.6185	0.0050	0.0004	0.0048	0.6287	6.7
	13	127	1.1674	0.0095	0.0006	0.0091	1.1865	12.7
Surin	14	79	0.7283	0.0059	0.0009	0.0056	0.7407	7.9
Sakon Nakhon	15	75	0.6917	0.0056	0.0005	0.0054	0.7031	7.5
Chaiyaphum	16	75	0.6917	0.0056	0.0000	0.0054	0.7027	7.5
Buri Ram	17	33	0.3075	0.0025	0.0004	0.0024	0.3128	3.3
	18	22	0.2069	0.0016	0.0005	0.0016	0.2106	2.2
Roi Et	19	60	0.5545	0.0045	0.0002	0.0043	0.5635	6
Loei	20	54	0.4996	0.0040	0.0012	0.0039	0.5086	5.4
Total		1,626	14.9752	0.1212	0.0105	0.1161	15.2231	162.6

*M$ = Million United States Dollars.

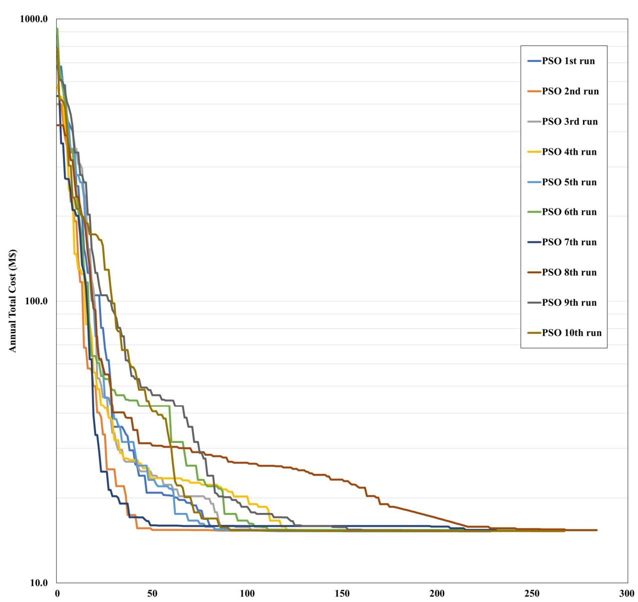

FIGURE 6. Statistical Analysis of Optimization Process (10 Executions).

V. Conclusions

This paper proposes a methodology for optimizing the size and location of electric vehicle charging stations. The proposed approach utilizes a comprehensive dataset encompassing geographic information, high-voltage substation data, highway road data, and urban road data to determine the optimal capacity and location of FCSs, with the objective of minimizing the total cost of charging station development and considering electric power system constraints. The total cost encompasses investment costs, operation and maintenance costs, electrical grid loss costs, and electric power system reliability costs. The cost of electrical grid loss significantly impacts the optimal size and location of the FCSs, as their placement directly affects transmission system losses. Locating FCSs closer to the generation source minimizes electrical grid loss costs within the electrical system. Therefore, the accurate incorporation of electrical grid loss into the optimization process is outstanding. Electric power system reliability is crucial for the power system. Therefore, the optimal size and placement of FCSs must minimize their impact on electric power system reliability. Beyond ensuring the power system's operational security, our approach efficiently identifies the optimal placement and size of FCSs at minimal cost. Furthermore, rapid and accurate convergence to optimal solutions is facilitated by the method. Importantly, adherence to the rigorous criteria established by the TSO is achieved by the resulting power system reliability. In future work, integrating machine learning techniques for accurate forecasting of EVs demand profiles could significantly enhance the proposed approach for optimizing the size and placement of FCSs, enabling more effective service to EV users.

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