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Charging Station Placement for Electric Vehicles: A Case Study of Guwahati City, India

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ABSTRACT The ever-increasing population of India accompanied by the recent concerns regarding fossil fuel depletion and environmental pollution has made it indispensable to develop alternate mode of transportation. Electric vehicle (EV) market in India is expanding. For acceptance of EVs among the masses, development of charging infrastructure is of paramount importance. This paper formulates and solves the charging infrastructure-planning problem for Guwahati, India, that will develop as a smart city soon. The allocation of charging station problem was framed in a multi-objective framework considering the economic factors, power grid characteristics, such as voltage stability, reliability, power loss, as well as EV user’s convenience, and random road traffic. The placement problem was solved by using a Pareto dominance-based hybrid algorithm amalgamating chicken swarm optimization (CSO) and the teaching learning-based optimization (TLBO) algorithm. Finally, the Pareto optimal solutions were compared by fuzzy decision-making.

INDEX TERMS City, cost, charging station, electric vehicle, optimization, traffic.

NOMENCLATURE

Constant Parameters

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_R$</td>
<td>Congestion probability of residential area</td>
</tr>
<tr>
<td>$P_O$</td>
<td>Congestion probability of office area</td>
</tr>
<tr>
<td>$C_{fast}$</td>
<td>Installation cost of fast charging stations</td>
</tr>
<tr>
<td>$C_{slow}$</td>
<td>Installation cost of slow charging stations</td>
</tr>
<tr>
<td>$C_{P_{fast}}$</td>
<td>Power consumption of fast charging stations</td>
</tr>
<tr>
<td>$C_{P_{slow}}$</td>
<td>Power consumption of slow charging stations</td>
</tr>
<tr>
<td>$P_{elec}$</td>
<td>Per unit cost of electricity</td>
</tr>
<tr>
<td>$m$</td>
<td>Maximum number of locations in which charging station will be placed</td>
</tr>
<tr>
<td>$q$</td>
<td>Total number of charging demand points</td>
</tr>
<tr>
<td>$w_1$</td>
<td>Weight assigned to V</td>
</tr>
<tr>
<td>$w_2$</td>
<td>Weight assigned to R</td>
</tr>
<tr>
<td>$w_{21}$</td>
<td>Weight assigned to SAIFI</td>
</tr>
<tr>
<td>$w_{22}$</td>
<td>Weight assigned to SAIDI</td>
</tr>
<tr>
<td>$w_{23}$</td>
<td>Weight assigned to CAIDI</td>
</tr>
<tr>
<td>$w_3$</td>
<td>Weight assigned to Power loss</td>
</tr>
</tbody>
</table>

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VSI_{base} | Base value of Voltage Stability Index |
SAIFI_{base} | Base value of SAIFI |
SAIDI_{base} | Base value of SAIDI |
CAIDI_{base} | Base value of CAIDI |
$P_{loss}$ | Base value of power loss |
$N_D$ | Total number of buses of the distribution network |
$F_{max}$, $f_{max}$ | Maximum number of fast charging stations and charging points |
$S_{max}$, $s_{max}$ | Maximum number of slow charging stations and charging points |
$Q_{min}$ | Lower limit of reactive power of bus i |
$Q_{max}$ | Upper limit of reactive power of bus i |
$P_{min}$ | Lower limit of active power of bus i |
$P_{max}$ | Upper limit of active power of bus i |
$\lambda_f$, $\lambda_s$ | Arrival rate of EVs in fast and slow charging stations |
$\rho_f$, $\rho_s$ | Utilization rate of fast and slow charging stations |
$P^f_0$, $P^s_0$ | Probability of no EVs waiting in fast & slow charging stations |
I. INTRODUCTION

EVs have emerged as a transportation mode free from local emissions. India being a signatory of the Paris agreement is planning to be an EV nation by 2030 [1]. However, absence of easily accessible charging stations is one of the encumbrances affecting the EV market in India. Therefore, the government of India has recently started taking many initiatives for development of sustainable and easily accessible charging stations [1]. Inappropriate positioning of charging stations may affect smooth operation of the power grid causing voltage instability, increased power loss, harmonics and lower reliability indices [2], [3]. Additionally, charging stations should be easily accessible to EV drivers preferably causing no extra congestion. The complex and haphazard nature of the power grid and road network of India makes the charging infrastructure-planning problem a tedious and challenging task. Motivated by the recent concerns related to environmental pollution and energy crisis, we make an attempt to formulate and solve the charging station allocation problem in the context of Guwahati city, India. Guwahati is one of the upcoming smart cities [1]. Hence, it is expected that in future, a large number of EVs will ply on the roads of Guwahati resulting in necessity of charging stations.

Charging station placement problem concerns researchers across the world. Deb et al. [1] reviewed various aspects of charging infrastructure planning like global scenario, modeling approaches, objective functions, and constraints.

The charging station placement problem is formulated considering only transport network in [4]–[6]. Liu et al. [4] considered construction cost and running cost as the objective functions along with the charging need as a constraint in their formulation. They applied Adaptive Particle Swarm optimization (APSO) for solving the complex problem.
The aforesaid approach was tested on a road network of Beijing. Bendia Abdellah et al. [5] formulated the charging station allotment problem for the city of Cologne in Germany. They considered installation cost and cost of commuting the distance between charging demand point and charging stations as objective functions. The allocation problem was solved by a hybrid method amalgamating k means of clustering and Genetic Algorithm (GA). Tu et al. [6] formulated the charging infrastructure planning problem for a road network of Shenzhen city in China. They considered maximization of travel time of EVs and minimization of waiting time in the charging stations as the objective functions. The range of EV, capacity of charging stations, time required for charging were considered as constraints in the planning model. The allocation problem was solved by applying GA.

References [7]–[9] have formulated the charging station placement problem by considering only distribution network. Liu et al. [7] have presented an approach for placing the charging stations considering cost as the objective function for IEEE 123 bus test network. Modified Primal Dual Interior Point Algorithm (MPDIPA) was utilized for solving the placement problem. Zheng et al. [8] presented a unique scheme for charging and battery swapping station placement considering cost as the objective function and power consumption limit, voltage limit, current limit as constraints. A modified version of Differential Evolution (DE) was utilized for solving the placement problem. The authors tested the proposed approach on IEEE 15 and IEEE 43 bus distribution network. Simorgh et al. [9] considered the cost and demand response as the objective functions and solved the placement problem by applying PSO. Further, they showed that demand response program can reduce grid losses and the total cost.

On the contrary, references [10]–[12] modeled the placement problem in a multi-disciplinary approach by giving consideration to both transport and distribution network. Wang et al. [10] used a multi-objective EV charging station planning model ensuring charging service and simultaneously considering power loss and voltage deviation of the distribution network. The placement problem was solved by using Data Envelopment Analysis (DEA) as well as by a Cross-Entropy based method (CE). The authors validated the proposed approach on superimposed IEEE 33 bus distribution network and 25 node road network. Rajabi-Ghahnavieh and Sadeghi-Barzani [11] modeled the charging station placement problem for northwest Tehran, Iran. They considered zonal traffic circulation in the formulation of charging station placement along with station development cost and grid operator cost. Subsequently, the problem was solved by using GA. Deb et al. [12] modeled the charging station allotment problem with cost as the objective function where the characteristics of the distribution network such as voltage deviation, reliability and power losses were also taken into account in the planning model by enforcing penalty for infringing the safe limits of these factors. Further, a novel CSO TLBO algorithm was applied for obtaining the apposite sites of the charging stations. The proposed approach was validated on superimposed IEEE 33 bus distribution network and 25 node road network.

References [4]–[12] highlight the contributions of contemporary researches in the arena of charging station placement. However, the existing studies on charging station planning fail to take into account some of the key factors such as resiliency of distribution network, waiting time in the charging stations, and traffic intensity. Moreover, only few studies formulate the placement problem in the context of an Indian city. Compared with the existing research works related to charging infrastructure planning, the main contributions of the present work are:

1. The present work models the charging station placement problem in the context of Guwahati, India. Guwahati is one of the upcoming smart cities of India. In future, a large number of EVs will ply on the roads of Guwahati. Hence, there will be necessity of sustainable charging infrastructure.
2. High traffic density along with low grid stiffness make it a challenging problem to find charger locations. Our work presents the approach, tools, and performance indicators to find optimal charger locations taking into account both the traffic and electric grid.
3. The work proposes a two stage-planning model for the charging station allotment. In the first stage, the candidate locations for placing the charging stations are identified by a novel methodology of Bayesian network. In the second stage, optimization is performed to select the best locations, type of charging stations and number of charging points at the charging stations.

II. CHARGING STATION PLACEMENT PROBLEM
Solving the charging station placement problem requires the positioning of the charging stations in the road network considering economic factors, operating parameters of the power grid, and EV users’ ease. The present work utilizes a two-stage modeling of the charging station placement problem as illustrated in the subsequent sub-sections. It is expected that the two-stage planning model will reduce the computational time and effectively locate the charging stations.

A. SCREENING OF THE CANDIDATE LOCATIONS FOR CHARGING STATION PLACEMENT
In the first stage, the potential locations for the placement of charging stations is determined by using a probabilistic approach based on Bayesian network [13]–[17]. It seems to be a common practice to situate the charging stations at the meeting points of distribution and road network [10], [12]. Thus, we can say that the superimposed nodes or the nodes of the road network adjacent to the buses of the distribution network are the candidate sites for the assignment of charging stations. However, some of these nodes can be crammed with high traffic intensity. Also, the chance of some of these nodes being vulnerable points of the grid in terms of voltage stability cannot be disregarded. In the present work, distance of the
road network nodes from the nearest bus of the distribution network, traffic intensity and grid stability are considered as key factors for finding the candidate sites for placing the charging stations. The potential of Bayesian network to deal with uncertainty and interaction among different events is used in the present work. The Bayesian network utilized in the present work to find the candidate locations for the placement of charging stations is as shown in Fig. 1.

![Bayesian Network for finding candidate sites for charging station placement.](image1)

The Bayesian network has three parent nodes [13] named ‘Congestion’, ‘Voltage Sensitivity Factor (VSF)’ and ‘Distance’. As shown in Fig. 1 ‘Candidate’ is the child node [13] of ‘Congestion’, ‘Voltage Sensitivity Factor (VSF)’ and ‘Distance’. The states of ‘Congestion’ are {Low, High}, states of ‘VSF’ are {Low, Medium, High}, states of ‘Distance’ are {Low, Medium, High} and the states of the child node ‘Candidate’ are {Yes, No}. The probability that a particular node is a candidate location is computed by bucket elimination algorithm [14]–[17] as given by Eq. (1).

\[
P(candidate = yes) = P(candidate|VSF, congestion, distance) \\
			\times P(VSF) \times P(congestion) \times P(distance) \quad (1)
\]

The distance of the node of the road network from the nearest bus of the distribution network is calculated graphically. The computational procedures for finding VSF, congestion probability are elaborated as follows:

1. **VSF-** The present work uses VSF for analyzing the stability of the distribution network. VSF is defined as the ratio of variation in voltage and variation in load [18].

\[
VSF = \left|\frac{dV}{dP}\right| \quad \forall P < P_{max} \quad (2)
\]

The forward and backward sweep algorithm [19] is used for determining the voltage of the buses of the distribution network. The maximum value of load for which the load flow converges is called realistic loading margin of the system. The computation of realistic loading margin is necessary to ascertain how vulnerable the system is to change of load. The flowchart illustrating the procedure to compute VSF and realistic loading margin is shown in Fig. 2.

2. **Congestion Probability-** A probabilistic approach based on Bayesian network is utilized in the present work for finding the probability of congestion of the nodes of the road network. The Bayesian network model used for finding congestion probability is shown in Fig. 3. The probability of a road network being congested depends on the traffic flow that in turn depends on day of the week, time of the day, and area covered by the road. Thus, ‘Day’, ‘Time’, and ‘Area’, are the parent nodes [13] of the Bayesian network. And, ‘Traffic Flow’ is the child node [13] of the nodes ‘Day’, ‘Time’, and ‘Area’. Similarly, ‘Congestion’ is the child node of ‘Traffic Flow’. The probability of congestion being high or low is computed by bucket elimination algorithm [13]–[17]. The states of the root nodes ‘Day’, ‘Time’, and ‘Area’ are {Weekday, Weekend}, {AM Peak, Work, PM Peak, Leisure, Rest}, {Residential (R), Office (O), Market (M), School (Sc)} respectively. The states of the child node ‘Traffic flow’ are {Low (L), Medium (M), High (H)}. The states of the node
‘Congestion’ are \{Low (L), High (H)\}. The congestion probabilities of residential and Office areas are:

\[
P_R = \frac{P(\text{Area} = \text{R})}{P(\text{congestion} = \text{H})} \quad (3)
\]

\[
P_O = \frac{P(\text{Area} = \text{O})}{P(\text{congestion} = \text{H})} \quad (4)
\]

The congestion probabilities of other areas can be found by replacing the numerator of Eq. (3) and Eq. (4) accordingly based on area.

### B. OPTIMIZATION

The second stage of the proposed planning model involves finding the best or optimal locations for the placement of charging stations \(p\) from the set of candidate locations \(p_c\), number of fast/ slow charging stations \((F_p, S_p)\) and the number of fast/ slow charging points or servers \((f_p, s_p)\). Thus, the decision variables of the optimization problem are:

\[
p = \{p_1, p_2, \ldots, p_m\}
\]

\[
F_p = \{F_1, F_2 \ldots F_m\}
\]

\[
S_p = \{S_1, S_2 \ldots S_m\}
\]

\[
f_p = \{f_1, f_2 \ldots f_m\}
\]

\[
s_p = \{s_1, s_2 \ldots s_m\}
\]

where \(m\) is the maximum number of locations for the placement of charging stations. The placement problem is formulated as a multi-objective optimization problem with cost, VRP index, accessibility index and waiting time in the charging stations as objective functions. An overview of the multi-objective formulation with objective functions and constraints is presented in this section.

The objective functions and constraints of the placement problem are elaborated as follows:

1. Cost-The optimization concerns the curtailment of the installation and operation cost

\[
\text{Cost} = C_{\text{installation}} + C_{\text{operation}}
\]

\[
C_{\text{installation}} = \left\{ \sum_{i=1}^{m} F_i \times f_i \right\} \times C_{\text{fast}} + \left\{ \sum_{i=1}^{m} S_i \times s_i \right\} \times C_{\text{slow}}
\]

\[
C_{\text{operation}} = \left\{ \sum_{i=1}^{m} F_i \times f_i \right\} \times C_{\text{P_{fast}}}
\]

\[
+ \left\{ \sum_{i=1}^{m} S_i \times s_i \right\} \times C_{\text{P_{slow}}} \times P_{\text{elec}}
\]

From Eq. (6) it can be inferred that the installation cost depends on the cost of installing fast and slow chargers, number of fast and slow charging stations, as well as number of fast and slow charging points. Similarly, from Eq. (7) it can be inferred that the operation cost depends on the power consumption of fast and slow chargers, per unit cost of electricity, number of fast and slow charging stations, as well as number of fast and slow charging points. The installation and operation cost is a function of number of fast and slow charging stations as well as number of fast and slow charging points.

2. VRP index-The second objective function is the minimization of VRP index [1]. VRP index is a composite index formulated by Deb et al. [1] that takes into account distribution network operating parameters such as voltage stability, reliability, and power loss together under a single frame. One more salient feature of the VRP index is that it takes into account both frequency and duration based reliability indices. The suitable value, such as minimum or maximum of the VRP index cannot be generalized and is dependent on the test network. A low value of VRP index is desirable. Ideally, the minimum value of VRP index is 1 when there is no congestion. From Eq. (8)

\[
VRP = f(p, F_p, S_p, f_p, s_p) = w_1V + w_2R + w_3P
\]

where

\[
V = \frac{\text{VSI}}{\text{VSI}_{\text{base}}}
\]

\[
P = \frac{P^1_{\text{loss}}}{P^\text{base}_{\text{loss}}}
\]

\[
R = w_{21}\frac{\text{SAIFI}_{\text{base}}}{\text{SAIFI}_{\text{base}}} + w_{22}\frac{\text{SAIDI}_{\text{base}}}{\text{SAIDI}_{\text{base}}}
\]

\[
+ w_{23}\frac{\text{CAIDI}_{\text{base}}}{\text{CAIDI}_{\text{base}}}
\]

\[
\text{VSI}_{\text{base}} = \sum_{i=1}^{N_D} 2V_i^2 \lambda_i^2 - 2V_i^2P_{i+1}r_i + Q_i^2x_i
\]

\[
- \lambda_i^2(P_{i+1}^2 + Q_i^2)
\]

\[
P_p^i = P_p + \{(F_p \times f_p) \times C_{\text{P_{fast}}}\}
\]

\[
+ \{(S_p \times s_p) \times C_{\text{P_{slow}}}\}
\]

\[
\text{SAIFI}_{\text{base}} = \sum_{i=1}^{N_D} \lambda_i^2 N_i
\]

\[
\text{SAIDI}_{\text{base}} = \sum_{i=1}^{N_D} U_i^2 N_i
\]

and

\[
\text{CAIDI}_{\text{base}} = \sum_{i=1}^{N_D} \lambda_i^2 N_i
\]

\[
\text{SAIFI} = \frac{\sum_{i=1}^{N_D} \lambda_i^2 N_i}{\sum_{i=1}^{N_D} N_i}
\]

\[
\text{SAIDI} = \frac{\sum_{i=1}^{N_D} U_i^2 N_i}{\sum_{i=1}^{N_D} N_i}
\]

and

\[
\text{CAIDI} = \frac{\sum_{i=1}^{N_D} \lambda_i^2 N_i}{\sum_{i=1}^{N_D} N_i}
\]
From Eq. (8) it is seen that VRP is a function of the position where charging stations are placed, type of charging stations, number of charging stations and charging points. Eq. (9) and Eq. (11) mathematically describes the voltage stability index before and after the placement of charging stations. Eq. (10) is used for computing the increase in load due to EV charging stations. Eq. (12) and Eq. (13) is used to compute the reliability indices such as SAIFI, SAIDI, and CAIDI before and after the placement of charging stations. From Eq. (12) and Eq. (13) it is seen that SAIFI is a frequency based reliability index and it depends on the frequency of interruption. On the other hand, SAIDI is a duration based reliability index and it depends on the duration of interruption. The frequency and duration of interruption after the placement of charging stations is calculated by unitary method as shown in Eq. (14). Eq. (15) explains the computation of power loss before and after the placement of charging stations.

3. Accessibility index-The Accessibility of the charging stations is chosen as the third objective function. For computation of accessibility (A) the distance matrix (D) and reduced distance matrix (DD) first need to be computed. The distance matrix, D gives the distance between the charging point demand and charging stations. And, reduced distance matrix, DD identifies the nearest charging stations for each of the charging point demand and gives the distance between the charging point demand and its nearest charging station. D, DD, d and A are computed as follows:

$$D = \begin{bmatrix} d_{1c_1} & d_{1c_2} & \ldots & d_{1c_m} \\ d_{2c_1} & d_{2c_2} & \ldots & d_{2c_m} \\ \vdots & \vdots & \ddots & \vdots \\ d_{q_c1} & d_{q_c2} & \ldots & d_{q_cm} \end{bmatrix}$$

$$DD = \begin{bmatrix} \min(d_{1c_1}, d_{1c_2}, \ldots, d_{1c_m}) \\ \min(d_{2c_1}, d_{2c_2}, \ldots, d_{2c_m}) \\ \vdots \\ \min(d_{q_c1}, d_{q_c2}, \ldots, d_{q_cm}) \end{bmatrix}$$

$$d = \sum_{i=1}^{q} DD_i$$

$$A = \frac{1}{|d|}$$

4. Waiting time

The waiting time ($W_t$) in the charging stations cause inconvenience to the EV drivers. Hence, the optimization aims to minimize the waiting time. In the present work, the waiting time in the charging stations is modeled by M/M/c queuing theory [20]–[22]. The waiting times in the fast and slow charging stations are:

$$W_f = \frac{\sum_{i=1}^{m} \frac{p_i^f + 1}{(l - 1)!}}{\lambda_f} \times P_0$$

$$W_s = \frac{\sum_{i=1}^{m} \frac{p_i^s + 1}{(l - 1)!}}{\lambda_s} \times P_0$$

From Eq. (17) and Eq. (18) it can be inferred that the waiting time in the charging stations depends on the number of charging points or servers in the charging stations.

5. Constraints

The different constraints of the charging station placement problem are as follows:

$$0 < F_p \leq F_{\text{max}} \quad \text{and} \quad 0 < \rho_p \leq \rho_{\text{max}}$$

$$0 < S_p \leq S_{\text{max}} \quad \text{and} \quad 0 < \rho_p \leq \rho_{\text{max}}$$

$$P_i^\text{min} \leq P_i \leq P_i^\text{max}$$

$$Q_i^\text{min} \leq Q_i \leq Q_i^\text{max}$$

$$P_{gi} - P_{di} - V_i \sum_{j=1}^{N_D} V_j Y_{ij} \cos(\delta_i - \delta_j - \theta_{ij}) = 0$$

$$Q_{gi} - Q_{di} - V_i \sum_{j=1}^{N_D} V_j Y_{ij} \cos(\delta_i - \delta_j - \theta_{ij}) = 0$$

Eq. (19) and Eq. (20) takes into account the maximum and minimum number of fast as well as slow charging stations and charging points that can be placed. Eq. (21) and Eq. (22) takes into account the upper and lower limits of active and reactive power respectively. Eq. (23) and Eq. (24) considers the power balance equation.

III. OPTIMIZATION ALGORITHMS

A multi-objective hybrid CSO-TLBO algorithm presented in [23] was harnessed to solve the optimisation problem. CSO is a swarm intelligence inspired algorithm that mimics the behaviour of chicken swarm. TLBO is a Nature Inspired Optimization (NIO) algorithm that mimics the teaching and learning process. The implementation of CSO and TLBO for solving the optimization problem is explained by Algorithm 1 and Algorithm 2 respectively. The grading mechanism of CSO is amalgamated with TLBO to improve the utilization rate of population and convergence speed of the algorithm. It is expected that amalgamation of CSO with TLBO reduces the chances for premature convergence of CSO in computationally expensive problems. Being hybrid algorithm, TLBO is activated for all the generation and CSO is invoked periodically depending on the value of an algorithm-specific control parameter named INV. The flowchart for implementing multi-objective CSO TLBO is shown in Fig. 4. The computation of rank and crowding distance can be found in [23].
Algorithm 1 Pseudo Code of Multi-Objective CSO [23]

Initialize the population of chicken having size PN and define other algorithm specific parameters such as G, size of rooster, hen, and mother hen;

Evaluate the rank of PN chicken, \( t = 0 \), establish the hierarchal order in the swarm based on rank and form mother child relationship;

While \( (t < \text{gen}) \)
\( t = t + 1 \);
If \( (r\%G == 0) \)
Establish the hierarchal order in the swarm as well as mother child relationship;
Else
For \( i = 1:PN \)
If \( i == \text{rooster} \)
Update its solution by:
\[
S_i^{t+1} = S_i^t + S1 \times \text{rand} \times (x_{i1}^{t} - x_{i,j}^{t}) + S2 \times \text{rand} \times (x_{i2}^{t} - x_{i,j}^{t})
\]
% where \( S1 = \exp(\frac{f_i - f_{11}}{\text{abs}(f_i) + \varepsilon}) \)
\( S2 = \exp(f_{i2} - f_i) \)
End if
If \( i == \text{hen} \)
Update its solution by:
\[
S_{i,j}^{t+1} = S_{i,j}^t + S1 \times \text{rand} \times (x_{i1,j}^{t} - x_{i,j}^{t}) + S2 \times \text{rand} \times (x_{i2,j}^{t} - x_{i,j}^{t})
\]
% where \( S1 = \exp(\frac{f_i - f_{11}}{\text{abs}(f_i) + \varepsilon}) \)
\( S2 = \exp(f_{i2} - f_i) \)
End if
If \( i == \text{chick} \)
Update its solution by:
\[
x_{i,j}^{t+1} = x_{i,j}^t + FL \times (x_{m,j}^t - x_{i,j}^t)
\]
% where \( x_{m,j}^t \) represents the position of the \( j \)-th chick’s mother. FL is a parameter signifying that the chick would follow its mother. FL is generally chosen in between 0 and 2
End if
Compute the rank of all the individual of the population
If rank \( (t) < \) rank \( (t - 1) \)
Update the solution
End if
Else
Retain the existing solution
End if
End for
End while

Algorithm 2 Pseudo Code of Multi-Objective TLBO [23]

Set \( k = 1; \)
Initialize the population size(PN) and generate the initial population of students randomly;
Compute the rank for all the individuals of the population;
while \( (k < \text{gen}) \)
\{Teacher Phase\}
Assign the teacher \( (T_k) \) based on the rank;
for \( i = 1:PN \)
Update each learner by:
\[
Z_{new} = Z_{old} + \text{rand} \times (T_k - R_{i,m})
\]
% where \( \text{rand} \) is a random number, \( R_{i,m} \) is random number between 0 and 2, \( m \) is mean of the decision variable vector
Compute the rank of all the individual of the population;
If rank \( (t) < \) rank \( (t - 1) \)
Update the solution;
End if
Else
Retain the existing solution
End if
End for
\{End of teacher phase\}
\{Learner Phase\}
Choose two learners \( Z_i \) and \( Z_j \), \( i \neq j; \)
if(\text{fitness of } Z_i \text{ better than } Z_j) \)
Replace \( i \)-th learner by \( Z_{new} = Z_{old} + \text{rand} \times (Z_i - Z_j) \); \% \( \text{rand} \) is a random number
End if
Else
Replace \( i \)-th learner by \( Z_{new} = Z_{old} + \text{rand} \times (Z_j - Z_i) \);
End if
End for
Compute the rank of all the individual of the population
If rank \( (t) < \) rank \( (t - 1) \)
Update the solution
End if
Else
Retain the existing solution
End if
End for

End while

References
IV. SOLUTION PROCEDURE

The procedure for solution of the charging station placement problem is as follows- **Step 1**: Initialization

**Step 1.1**: Input data. Input the road network, distribution network data, upper and lower limits of different constraints and set the different algorithm specific parameters of CSO and TLBO

**Step 1.2**: Generate feasible initial population randomly. The initial feasible population is of the form

\[
P_{\text{init}} = [A_{\text{pop}} B_{\text{pop}} C_{\text{pop}} D_{\text{pop}} E_{\text{pop}}]
\]

where \( A_{\text{pop}} = \begin{bmatrix} p_{11} & p_{12} & p_{13} & \cdots & p_{1m} \\ p_{21} & p_{22} & p_{23} & \cdots & p_{2m} \\ p_{31} & p_{32} & p_{33} & \cdots & p_{3m} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ p_{PN1} & p_{PN2} & p_{PN3} & \cdots & p_{Pnm} \end{bmatrix} \)

\( B_{\text{pop}} = \begin{bmatrix} f_{p_{11}} & f_{p_{12}} & f_{p_{13}} & \cdots & f_{p_{1m}} \\ f_{p_{21}} & f_{p_{22}} & f_{p_{23}} & \cdots & f_{p_{2m}} \\ f_{p_{31}} & f_{p_{32}} & f_{p_{33}} & \cdots & f_{p_{3m}} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ f_{p_{PN1}} & f_{p_{PN2}} & f_{p_{PN3}} & \cdots & f_{p_{Pnm}} \end{bmatrix} \)

\( C_{\text{pop}} = \begin{bmatrix} S_{p_{11}} & S_{p_{12}} & S_{p_{13}} & \cdots & S_{p_{1m}} \\ S_{p_{21}} & S_{p_{22}} & S_{p_{23}} & \cdots & S_{p_{2m}} \\ S_{p_{31}} & S_{p_{32}} & S_{p_{33}} & \cdots & S_{p_{3m}} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ S_{p_{PN1}} & S_{p_{PN2}} & S_{p_{PN3}} & \cdots & S_{p_{Pnm}} \end{bmatrix} \)

\( D_{\text{pop}} = \begin{bmatrix} F_{p_{11}} & F_{p_{12}} & F_{p_{13}} & \cdots & F_{p_{1m}} \\ F_{p_{21}} & F_{p_{22}} & F_{p_{23}} & \cdots & F_{p_{2m}} \\ F_{p_{31}} & F_{p_{32}} & F_{p_{33}} & \cdots & F_{p_{3m}} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ F_{p_{PN1}} & F_{p_{PN2}} & F_{p_{PN3}} & \cdots & F_{p_{Pnm}} \end{bmatrix} \)

\( E_{\text{pop}} = \begin{bmatrix} s_{p_{11}} & s_{p_{12}} & s_{p_{13}} & \cdots & s_{p_{1m}} \\ s_{p_{21}} & s_{p_{22}} & s_{p_{23}} & \cdots & s_{p_{2m}} \\ s_{p_{31}} & s_{p_{32}} & s_{p_{33}} & \cdots & s_{p_{3m}} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ s_{p_{PN1}} & s_{p_{PN2}} & s_{p_{PN3}} & \cdots & s_{p_{Pnm}} \end{bmatrix} \)

A randomly generated initial solution is feasible if it satisfy all the constraints of charging station placement problem explained in section II (B)

**Step 1.3**: Evaluate the four objective functions cost, VRP index, accessibility and waiting time for the initial population. The rank and crowding distance were computed as in [23]. The first Pareto front with rank one is designated as \( T_k \)

**Step 2**: Run TLBO

**Step 2.1**: Run TLBO and update the solution based on rank and crowding distance [23]

**Step 2.2**: If the elements \( B_{\text{pop}} \) exceed \( F_{\text{max}} \), if the elements of \( C_{\text{pop}} \) exceed \( S_{\text{max}} \) then those elements are made equal to \( F_{\text{max}} \) and \( S_{\text{max}} \) respectively. Similarly, if the elements of \( D_{\text{pop}} \) exceed \( f_{\text{max}} \), if elements of \( E_{\text{pop}} \) exceed \( s_{\text{max}} \) then those elements are made equal to \( f_{\text{max}} \) and \( s_{\text{max}} \) respectively.

**Step 2.3**: Else, check feasibility of the solution. If the solution is infeasible repeat step 2.1 and 2.2 until feasible solution is obtained.

**Step 3**: Check whether the iteration count, \( t \) is divisible by \( \text{INV} \). If yes go to step 3.1. Else, go to step 3.5.

**Step 3.1**: If \( t \) is divisible by \( \text{INV} \) run CSO

**Step 3.2**: Run CSO and update the solution based on ranking and crowding distance

**Step 3.3**: Repeat step 2.2.

**Step 3.4**: Else, check feasibility of the solution. If the solution is infeasible repeat step 3.2 and 3.3 until feasible solution is obtained.

**Step 3.5**: Update the iteration count

**Step 4**: Check whether maximum generation count is reached. If maximum generation count is reached print the Pareto front. Else, repeat step 2 to step 4.

**Step 5**: Selection of the best compromise solution from the set of non-dominated solution is made by using the fuzzy decision making [24]–[26].

V. RESULTS

A. TEST SYSTEMS AND INPUT PARAMETERS

The present work solved the charging infrastructure planning problem for the city of Guwahati, India. Fig.5 shows
the highway network of Guwahati connecting Jalukbari with Narangi. Fig.6 shows the superimposed road and distribution network for the Guwahati city. The bus and line data of the distribution network are available in Ref [27]–[30] and the outage data of the distribution network were taken from the log book of the substations. The road network data were recorded from Google maps. The recorded traffic data from Google API was used for computing congestion probability of the road network nodes. The distance between the different nodes of the road network that was required for computing the Accessibility index (third objective function of the optimization problem) was also recorded from the Google maps. 24 hour traffic data was recorded for both weekdays and weekends. The characteristics of the nodes of the road network are reported in Table 1. Table 2 presents the different input parameters required for optimization. Table 3 presents the algorithm- specific control parameters of CSO TLBO.

### B. CANDIDATE LOCATIONS

At the first stage, the candidate locations for placement of the charging stations were screened by the methodology reported in section II (A). The VSF of the buses of the distribution network are reported in Table 4. The VSF of bus 19 was highest indicating that it was the weakest point of the power distribution network. The congestion probabilities of different types of the nodes of the road network computed by Bayesian network are reported in Table 5. The nodes sprawling market areas are heavily congested with congestion probability of 0.643. Table 6 reports the probability of being a candidate location for placement of charging stations for all the buses of the distribution network. The buses for which the probability of being candidate location was high were selected as the candidate locations for charging station placement as reported in Table 7. Assuming EV driving range of 150 km [31] and EVs completing 10 round trips from Jalukbari to Narangi, the charging demand nodes were computed as reported in Table 7. It should be noted that this work does not consider stochastic driving cycles reported in [32].

### C. OPTIMAL ALLOCATION OF CHARGING STATIONS

At the second stage, the optimal locations for the charging stations placement were selected from the set of candidate locations by solving the optimization problem reported in section II (B). The optimization problem was solved by using CSO TLBO algorithm. In this case, the optimization yielded

---

**TABLE 1.** Types of nodes of the road network.

<table>
<thead>
<tr>
<th>Node</th>
<th>Type</th>
<th>Node</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>School</td>
<td>8</td>
<td>Office</td>
</tr>
<tr>
<td>2</td>
<td>School</td>
<td>9</td>
<td>Residential</td>
</tr>
<tr>
<td>3</td>
<td>Residential</td>
<td>10</td>
<td>Market</td>
</tr>
<tr>
<td>4</td>
<td>Residential</td>
<td>11</td>
<td>Market</td>
</tr>
<tr>
<td>5</td>
<td>Residential</td>
<td>12</td>
<td>Market</td>
</tr>
<tr>
<td>6</td>
<td>Office</td>
<td>13</td>
<td>Market</td>
</tr>
<tr>
<td>7</td>
<td>Office</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
six non-dominated solution or planning schemes as shown in Table 8. Table 9 reports the values of the four objective functions for the six plans. From Table 9, it is clear that all the six plans were unique and it was tricky to select the best plan.

D. EFFECT OF CHARGING STATION PLACEMENT ON DISTRIBUTION NETWORK

The charging stations affect the operating parameters of the distribution network such as voltage deviation, reliability, and power loss. However, the voltage profiles of all the buses (Fig. 7) were within acceptable limit for all the six plans reported in Table 8. Fig. 8, Fig. 9 and Fig. 10 show the impact of charging station placement on the three reliability indices named SAIFI, SAIDI, and CAIDI respectively.

TABLE 4. VSF of the buses of distribution network.

<table>
<thead>
<tr>
<th>Bus no</th>
<th>VSF for critical loading</th>
<th>VSF for critical loading</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>0.1439</td>
<td>0.3966</td>
</tr>
<tr>
<td>3</td>
<td>0.1678</td>
<td>0.4217</td>
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<tr>
<td>4</td>
<td>0.1862</td>
<td>0.4346</td>
</tr>
<tr>
<td>5</td>
<td>0.1898</td>
<td>0.4247</td>
</tr>
<tr>
<td>6</td>
<td>0.2623</td>
<td>0.4499</td>
</tr>
<tr>
<td>7</td>
<td>0.2827</td>
<td>0.4704</td>
</tr>
<tr>
<td>8</td>
<td>0.2893</td>
<td>0.4573</td>
</tr>
<tr>
<td>9</td>
<td>0.2936</td>
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<tr>
<td>10</td>
<td>0.3601</td>
<td>0.5030</td>
</tr>
</tbody>
</table>

TABLE 5. Congestion probability of road network.

<table>
<thead>
<tr>
<th>Node type</th>
<th>Congestion Probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Market</td>
<td>0.645</td>
</tr>
<tr>
<td>Residential</td>
<td>0.259</td>
</tr>
<tr>
<td>School</td>
<td>0.283</td>
</tr>
<tr>
<td>Office</td>
<td>0.372</td>
</tr>
</tbody>
</table>

TABLE 6. Probability of being candidate location.

<table>
<thead>
<tr>
<th>Bus no</th>
<th>Probability</th>
<th>Bus no</th>
<th>Probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>0.717</td>
<td>11</td>
<td>0.015</td>
</tr>
<tr>
<td>3</td>
<td>0.667</td>
<td>12</td>
<td>0.01</td>
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<tr>
<td>4</td>
<td>0.011</td>
<td>13</td>
<td>0.001</td>
</tr>
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<td>5</td>
<td>0.001</td>
<td>14</td>
<td>0.627</td>
</tr>
<tr>
<td>6</td>
<td>0.741</td>
<td>15</td>
<td>0.371</td>
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<tr>
<td>7</td>
<td>0.726</td>
<td>16</td>
<td>0.445</td>
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<td>8</td>
<td>0.628</td>
<td>17</td>
<td>0.228</td>
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<tr>
<td>9</td>
<td>0.625</td>
<td>18</td>
<td>0.001</td>
</tr>
<tr>
<td>10</td>
<td>0.628</td>
<td>19</td>
<td>0.0001</td>
</tr>
</tbody>
</table>

TABLE 7. Candidate locations and charging demand nodes.

<table>
<thead>
<tr>
<th>Candidate Location (wrt to distribution network)</th>
<th>2</th>
<th>3</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>14</th>
</tr>
</thead>
<tbody>
<tr>
<td>Charging demand nodes (wrt to road network)</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>6</td>
<td>7</td>
<td>8</td>
<td>9</td>
<td>----</td>
</tr>
</tbody>
</table>

TABLE 8. Optimal allocation of charging stations.

<table>
<thead>
<tr>
<th>NDS</th>
<th>p</th>
<th>Fp</th>
<th>S0</th>
<th>Fp</th>
<th>S0</th>
<th>Fp</th>
<th>S0</th>
<th>Fp</th>
<th>S0</th>
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<td>10</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>10</td>
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</table>

TABLE 9. Objective function values for the planning schemes.

<table>
<thead>
<tr>
<th>Planning Scheme</th>
<th>Cost ($5\times10^6$)</th>
<th>VRP</th>
<th>A</th>
<th>W (hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5.0206</td>
<td>11.3011</td>
<td>0.0279</td>
<td>1.3603</td>
</tr>
<tr>
<td>2</td>
<td>8.8900</td>
<td>11.7391</td>
<td>0.1053</td>
<td>0.0807</td>
</tr>
<tr>
<td>3</td>
<td>7.1120</td>
<td>11.7018</td>
<td>0.0279</td>
<td>0.4165</td>
</tr>
<tr>
<td>4</td>
<td>7.9977</td>
<td>11.8097</td>
<td>0.0459</td>
<td>0.0730</td>
</tr>
<tr>
<td>5</td>
<td>5.0883</td>
<td>10.9291</td>
<td>0.0221</td>
<td>0.4103</td>
</tr>
<tr>
<td>6</td>
<td>5.9284</td>
<td>11.3119</td>
<td>0.0806</td>
<td>0.3448</td>
</tr>
</tbody>
</table>

D. EFFECT OF CHARGING STATION PLACEMENT ON DISTRIBUTION NETWORK

The charging stations affect the operating parameters of the distribution network such as voltage deviation, reliability, and power loss. However, the voltage profiles of all the buses (Fig. 7) were within acceptable limit for all the six plans reported in Table 8. Fig. 8, Fig. 9 and Fig. 10 show the impact of charging station placement on the three reliability indices named SAIFI, SAIDI, and CAIDI respectively.
The reliability indices degraded due to increased charging load. However, the degraded values were less than the critical values of these reliability indices reported in [33], [34]. The power losses of the distribution network after positioning the charging stations was also within acceptable limit as shown in Fig. 11. Thus, the two-stage planning model of charging station placement was capable of allocating charging stations with least harm to the distribution network of Guwahati.

**E. DECIDING BETWEEN PARETO OPTIMAL SOLUTIONS**

The final step was the selection among the plans. Selection of the best plan among the six plans was a tricky task due to involvement of opposing objectives. In real world, some criteria cannot be measured by crisp values due to indistinctness arising from human qualitative judgment [26]. Hence, a fuzzy evaluation system was used for the final decision making [26]. Cost, VRP index, accessibility index, and waiting time were chosen as the four aspects of decision making in the charging station placement problem. In the fuzzy decision making, low cost, VRP index, and waiting time received a higher evaluation. And, high accessibility received a higher evaluation. Table 10 lists the scale of the three objective functions based on the aforementioned criteria. The scores of each plan obtained by fuzzy evaluation system are reported in Table 11. Fig. 12 shows the radar charts for all the six planning schemes. The area occupied by plan 6 is highest indicating that it is the most beneficial plan. The area occupied by plan 2 and plan 3 is least indicating that they are the least convenient plan. Fig.13 shows the optimal locations of charging stations obtained by the best planning scheme (plan 6) and the charging demand points. In Fig. 13, the red
TABLE 10. Scale of fuzzy evaluation.

<table>
<thead>
<tr>
<th>Scale</th>
<th>Cost ($x10^5$)</th>
<th>VRP index</th>
<th>A/(km)</th>
<th>Wt (hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>7.1792</td>
<td>More than</td>
<td>11.92</td>
<td>0.0221</td>
</tr>
<tr>
<td>2</td>
<td>7.192-7.7161</td>
<td>More than</td>
<td>11.8320-</td>
<td>0.0221-</td>
</tr>
<tr>
<td>3</td>
<td>6.5422-7.192</td>
<td>11.7730-</td>
<td>0.0304-</td>
<td>0.8443-</td>
</tr>
<tr>
<td>4</td>
<td>5.9553-6.5422</td>
<td>11.7140-</td>
<td>0.0387-</td>
<td>0.7153-</td>
</tr>
<tr>
<td>5</td>
<td>5.3684-5.9553</td>
<td>11.6650-</td>
<td>0.0471-</td>
<td>0.5863-</td>
</tr>
<tr>
<td>6</td>
<td>4.7814-5.3684</td>
<td>11.5960-</td>
<td>0.0554-</td>
<td>0.4573-</td>
</tr>
<tr>
<td>7</td>
<td>4.1945-4.7814</td>
<td>11.5370-</td>
<td>0.0637-</td>
<td>0.3283-</td>
</tr>
<tr>
<td>8</td>
<td>3.6075-4.1945</td>
<td>11.4780-</td>
<td>0.0720-</td>
<td>0.1993-</td>
</tr>
<tr>
<td>9</td>
<td>3.0206-3.6075</td>
<td>10.9690-</td>
<td>0.0803-</td>
<td>0.0703-</td>
</tr>
<tr>
<td>10</td>
<td>Less than</td>
<td>Less than</td>
<td>11.4780</td>
<td>0.0887</td>
</tr>
</tbody>
</table>

TABLE 11. Score of the planning schemes.

<table>
<thead>
<tr>
<th>Plan</th>
<th>Cost</th>
<th>VRP index</th>
<th>A</th>
<th>Wt</th>
<th>Plan</th>
<th>Cost</th>
<th>VRP index</th>
<th>A</th>
<th>Wt</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>9</td>
<td>9</td>
<td>2</td>
<td>1</td>
<td>4</td>
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<td>3</td>
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<td>6</td>
<td>5</td>
<td>9</td>
<td>9</td>
<td>7</td>
</tr>
</tbody>
</table>

Triangles denote the charging stations and the black circles denote the charging demand points.

VI. CONCLUSION
Sustainable development of charging infrastructure is must to promote EVs. This work solved the charging station placement problem in the context of Guwahati city, an upcoming smart city. The charging station placement problem was modeled in a multi-objective framework considering cost, operating parameters of distribution network such as voltage stability, reliability, power loss, factors affecting EV driver’s convenience like accessibility to the charging stations, waiting time in the charging stations. A novel CSO TLBO algorithm was harnessed to solve the optimization problem. Fuzzy decision making was utilized to choose between various Pareto-optimal solutions. The results showed that the proposed approach is capable of allocating the charging stations with least harm to the operating parameters of the power distribution network and simultaneously considering EV drivers’ convenience. Moreover, the authors will try to reach the concerned authorities and implement the planning model on the entire Guwahati city as well as other Indian cities in future. Our future work will also address some of the critical issues related to charging infrastructure planning like pricing strategies in the charging stations, planning of Vehicle to Grid (V2G) enabled charging stations and planning of charging stations powered by renewable resources.

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REFERENCES


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