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Optimal Location of Fast Charging Station on Residential Distribution Grid

Prakornchai Phonrattanasak, *Member, IACSIT*, and Nopbhorn Leeprechanon

***Abstract*—The population of the Electric vehicle (EV) has been increasing rapidly worldwide due to its environmental friendly. However, there is a need to prepare effective electric charging station infrastructures to fill up battery for future day-to-day energy consumption. Then the electric charging station must be extensively installed to sufficiently serve a number of EVs, especially in metropolitan areas. Since electric charging station will be used simultaneously by many EVs and may lead to the unreliability of the distribution system. This paper therefore proposes an optimal location of fast charging station (FCS) on residential distribution grid aiming to minimize annual cost of power line loss, travelling cost of EVs in recharging, investment cost and variable cost of operation of FCS while maintaining system security. Ant colony optimization (ACO) is employed to minimize total cost by searching best location of FCS in a traffic area. A modified IEEE 69-bus system is used to verify the proposed technique. The results show that the proposed method found the optimal location of FCS on residential power distribution system with minimum cost while satisfying security constraints.**

***Index Terms*—Distribution system, electric vehicle, ant colony optimization and fast charging station.**

I. INTRODUCTION

The disadvantages of internal combustion in the vehicle engine are the negative impact on the environment, less efficiency and high a price of petroleum sources. Hybrid electric vehicle (HEV) and full EV have been developed rapidly. An EV is driven by electric motor using electrical energy stored in batteries or other energy storage devices [1]. The energy crisis of the mid 2000s stimulated the research and development of commercial EVs due mainly to the major concerns about rapid increase in oil prices and global warming crisis.

These EVs need batteries to be electrified by charging stations where they can be at home or public areas. An electric vehicle charging station, also called EV charging station, electric recharging point or electric vehicle supply equipment, is an important element in a Smart Grid infrastructure that supplies electric energy for future world's EVs population.

Within the various standards for plug-in vehicles and charging stations, charging method has been grouped into three basic levels:

Level 1 refers to single phase alternating current (AC) using grounded receptacles at the most commonly available voltages and currents. In North America this typically means 120V/16A, but in many parts of Europe it can mean up to 230V/16A.

Level 2 refers to single or triple phase AC 208-240V at current level up to 80A. The connector and charging cord are permanently fixed to the Level 2 charging station.

Level 3 refers to "*quick charge*" or *"fast charging"*. To achieve a very short charging period of time, Level 3 chargers supply very high voltages (300-500VDC) at very high currents (125-250 A).

A fully charge is possible for parking at home or at work but not for *"refueling"* in the middle of a trip. Two or eight hours are too long time to wait for a full charge when it is serviced by charging station level 1 or 2. Fast charging level 3 therefore makes more sense for most people who plan to own an EV car in which the charging period should not be over 15 minutes to get full charge [2]. Pairing this technology with charging point goes a long way towards making it feasible for mass acceptance. FCS should then be installed along the street like gas or petrol station while connected to the electric power distribution grid. However, it needs high power and must ensure the availability of supply for EVs consumption.

The impact of FCS on the connected distribution grid is an important point for power engineering [3], [4]. They must determine suitable location of FCS in order to reduce its impact on distribution grid. Loss in distribution grids should be low while the voltage of each bus and line loading limit is kept at an acceptable level. Another important factor that needs to be considered is the degree of traffic concentration of EVs. FCS should be placed in the location where a high degree of EVs traffic flow exists [5].

The focus of this paper is therefore on *Level 3* of FCS. The main purpose is to find optimal location of FCS connected on a distribution grid while satisfying power system security of residential distribution system and traffic constraints.

II. FAST CHARGING STATION

A. DC Fast Charging Station

The dc FCS requires three phase transformer that converts medium voltage to lower AC voltage levels [6, 7]. Then AC-DC power electronic stage converts AC into an intermediate DC voltage. Finally DC-DC power electronic stage convert intermediate DC voltage to the voltage required to charge the electronic vehicle battery. The dc fast charging circuit is shown in Fig. 1. Most dc fast charging has overall efficiency in 89-91%. Dc fast charging should be built to obtain almost unity power factor.

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Prakornchai Phonrattanasak is with Thammasat University, Thailand while holding an academic staff member at the North Eastern University, Thailand (e-mail: polratanasak.prakornchai@ gmail.com).

Nopbhorn Leeprechanon is with the Department of Electrical and Computer Engineering, Thammasat University, Thailand (e-mail: nopbhorn@ tu.ac.th).

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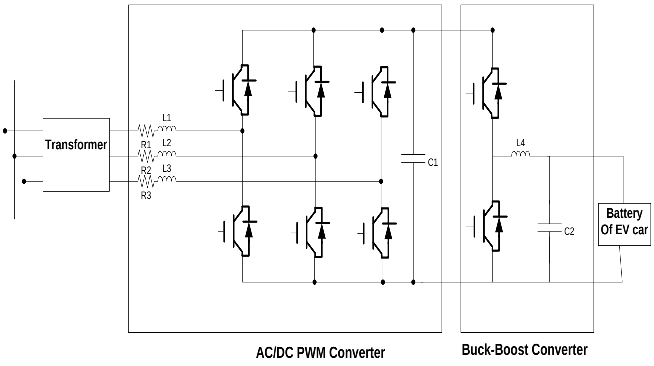

Fig. 1. The dc fast charging circuit

In this paper, the dc fast charging circuit is set up to 400 Volt, 250 Amp, 50 Hz and 100 kVA. One charging station contains 5 charging circuit or 500 kVA. The FCS looks like gas pump and is shown in Fig. 2.

Fig. 2. An example of dc fast charging station [6]

B. Power Flow in the Distribution System

Electric distribution system is the final stage in delivering electricity from the transmission system to consumers. Distribution system plays an important role in providing electric energy to dc FCSs through medium voltage transformers.

Power flow information in the distribution system is important for operation and planning of the system which presents the image of steady state operating condition. It provides information on the system operating condition at different loading levels for efficient and reliable operation of the system. It is envisaged that the power flow techniques are based on iterative techniques, which assume that the buses have 1.0 p.u. voltage magnitude and zero phase angle. The values are gradually updated to reach the final solution. This paper employs the backward-forward sweep distribution power flow [8,9] to obtain the system operating condition.

C. Quantity and Distribution Forecast of Electric Vehicle

Suppose there is an area of any shape for whom the leaving vehicles and the entering ones are equal in quantity, which is called the conversation of the number of vehicles [10, 11]. The large area can be divided into many small areas or defined areas where the number of electric vehicles is a constant. It can be viewed as a load point of charging station and the EVs from load point are always moving to the nearest station for charging as illustrated in Fig. 3. The total number of EVs can be obtained by predicting the population density, per capita vehicle ownership and the proportion of EVs.

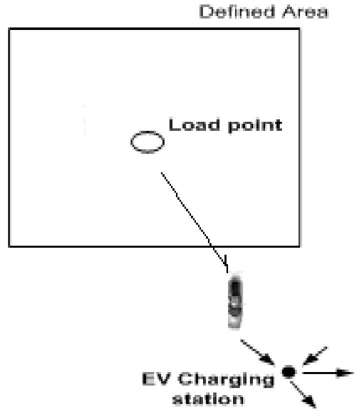

Fig. 3. Map of travelling of EV from load point to charging station in a defined area

The number of charging stations in studied area can be calculated from total number of EVs to be charged per day and other associated factors expressed as follow

$$n = \left[\frac{p \times e_a \times lfv \times chg\_time}{o \times f_1 \times f_2 \times q \times Cap \times lf \times \cos\phi} \right] \qquad (1)$$

where p is average charging power for each vehicle; e_a is total number of EVs to be charged per day ; lfv is daily load factor of vehicle; o is service time of EV charging station; chg_time is charging period of each vehicle; Cap is charging station capacity; q is the charging efficiency; f_1 is simultaneity factor of charging station; f_2 is demand factor of charging machine; lf is daily load factor of charging station; $\cos\phi$ is power factor of charging station; The bracket [ ] gives rounding number of n.

III. PROBLEM FORMULATION

Optimization algorithms can be used to find the optimal location of fast charging station units in a distribution grid. The method is applied on a system based on an existing grid topology with load data drawn from reliable measurements.

A. Objective Function

The objective function of the problem is formulated as follows.

1) Initial investment of charging station -Cinv, can be expressed as:

$$C_{inv} = \sum_{h=1}^{n} F \left[\frac{k(1+k)^m}{(1+k)^m - 1} \right] \qquad (2)$$

where n is the number of the new charging stations; F is the investment cost of charging station h; k is investment return rate namely the discount rate; m is the investment return period.

2) Annual variable operating cost of charging station - Cop, can be written as:

$$C_{op} = \sum_{h=1}^{n} \alpha F \tag{3}$$

where annual variable operating cost for charging station C_{op} include maintenance costs, material costs, staff salaries and electricity cost. It can be converted into the initial investment costs, of which α is a conversion coefficient.

3) Annual travelling cost or cost of wear and tear of EVs for recharging battery at charging station - Tc . can be stated as:

$$Tc = t\eta cz \sum_{h=1}^{n} \sum_{p \in P_h} g_{hp} L D_{hp} \tag{4}$$

where wear and tear cost considers a cost incurred from travelling of an EV to fast charging station in order to recharge battery during one year [10]; t is road twist coefficient; η is smooth traffic coefficient of road; L is loss coefficient; n is the number of charging stations; c is annual charging times per vehicle; z is turnaround coefficient; P_h stands for the collection that vehicle at point p moves to charging station h for charging; g_{hp} means parameters that vehicle at point p whether goes to charging station h for charging; D_{hp} is distance between charging station h and vehicle at point p.

4) Annual cost of energy loss in a line where FCS is installed in residential distribution system – Lc, can be calculated as:

$$Lc = 365 \times e \times o \times P_{Loss} \tag{5}$$

where e is electricity price per kilowatt per hour of power distribution system. P_{Loss} is real power loss in a line of the distribution system.

The real power loss in a line of the power distribution system can be expressed as following equation.

$$P_{Loss} = \sum_{i=1}^{\mathrm{N_B}} |I|^2 R_i \tag{6}$$

where I is current and R_i is the line resistance in line i respectively. $\mathrm{N_B}$ is the number of branch in electric distribution.

Minimizing the sum of C_{inv}, C_2, Tc and Lc is taken as objective to establish the model:

$$Min(C_{total}) = Min(C_{inv} + C_{op} + Tc + Lc) \tag{7}$$

where C_{total} is the total cost of annual investment costs, operating costs, travelling costs of EVs and costs of power loss in the power distribution lines when FCSs are installed.

B. Constraints

1) Constraints of the installed position of fast charging station

$$\sum_{h=1}^{n} g_{hp} = 1 \tag{8}$$

$$D_{ph} \le R_h \tag{9}$$

$$P_h < \frac{Cap_h \times lf(h) \times \cos\varphi_h \times o}{chg\_time \times lfv}, h = 1, 2, ..., n \tag{10}$$

where $lf(h)$ is the load factor of charging station h; Cap_h is capacity of charging station h; $\cos\varphi_h$ is power factor of charging station h; P_h is the total load of all vehicles go to station h for a daily charge; R_h is charging radius of charging station h and it is traffic constraint of FCS for EVs; $\sum_{h=1}^{n} g_{hp} = 1$ means that each vehicle goes to only one station for charging.

2) Security constraints of power distribution system

These incorporate the constraints of voltage magnitudes of all buses as well as distributed line loadings as follows:

$$V_i^{\min} \le V_i \le V_i^{\max}, i \in N_B \tag{11}$$

$$S_i \le S_i^{\max}, i \in N_S \tag{12}$$

S_i is line loading of each line in distribution grid. N_B is the number of bus in distribution system. N_S is the number of section in distribution system.

IV. SOLVING METHOD

A. Ant colony Optimization

Ant colony optimization (ACO) studies are inspired by the real ant colonies that are used to solve function or combinatorial optimization problem. Currently, most work has been done in the direction of applying ACO to combinatorial optimization. The first ACO system was introduced by Marco Dorigo [12] and was called “ant system”. Ant Colony Optimization, to some extent, mimic the behavior of real ants.

B. Apply ACO Algorithm for Problem Solving

The proposed algorithm works as follows: m ants are initially positioned on the node representing the first path. Each ant constructs one possible structure of the entire system. In fact, each ant builds a feasible solution (called a tour) by repeatedly applying a stochastic greedy search, called, *the state transition rule*. Once all ants have terminated their tour, the following steps are performed: The amount of pheromone is modified by applying the *global updating rule*. Ants are guided, in building their tours, by both heuristic information and by pheromone information. Naturally, a link with a high amount of pheromone is a very desirable choice. The pheromone updating rules are designed so that they tend to give more pheromone to edges, which should be visited by ants. Fig. 4 shows routes of ant between nest and food source in a 69 bus test system.

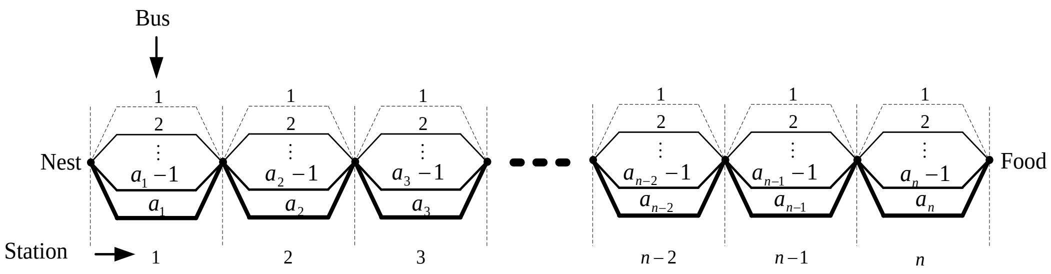

Fig. 4. Routes of ants between nest and food source

A flowchart of a conventional ACO algorithm is shown in Fig. 5 The detailed of ACO algorithm can be described in the following steps:

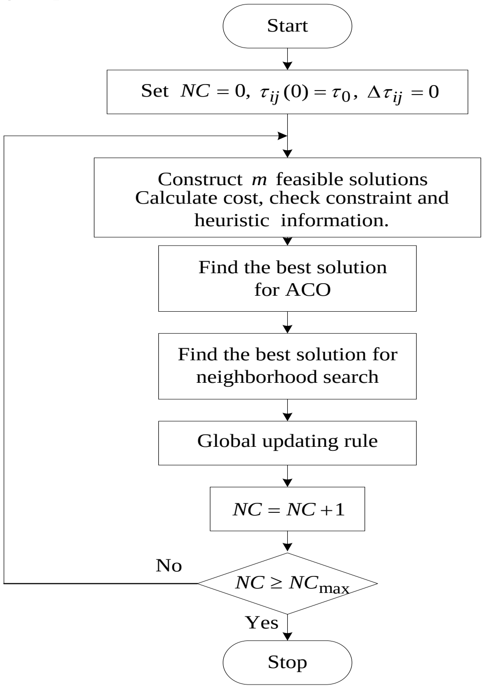

Fig. 5 Flow chart of ACO algorithm

```
Step 1. Initialization
    Set NC = 0     /* NC: cycle counter */
    For every combination (i,j)
        Set an initial value $\tau_{ij}(0)=\tau_0$ and $\Delta\tau_{ij}=0$
    End
Step 2. Construct feasible solutions
    For k=1 to m     /* m: number of ants */
        For i=1 to n  /* n: number of station */
            Choose a level of connection with transition

            probability given by Eq.(13).

        End
        Run distribution power flow
        Calculate Cost and Check Constraints
        Calculate heuristic information $\eta_{ij}$ by Eq.(14).
    End
    Update the best solution.
Step 3. Global updating rule
    For every combination (i,j)
        For k=1 to m
            Find $\Delta\tau_{ij}^k$ according to Eq.(17).
        End
        Update $\Delta\tau_{ij}$ according to Eq.(16).
    End
    Update the transition probability according to
    Eq.(15).
Step 4. Next search
    Set NC = NC+1
    For every combination (i,j)
        $\Delta\tau_{ij}=0$
    End
Step 5. Termination
    If (NC < $NC_{max}$) Then Go to step 2
    Else
        Print the best feasible solution.
    End.
```

To achieve the problem solving, following rules are needed to be expressed.

A. The State Transition Rule

The state transition rule is given in Eq. (13). This represents the probability when ant k selects station i and bus j :

$$p_{ij}^{k}(t)=\frac{\left[\tau_{ij}(t)\right]^{\alpha}\left[\eta_{ij}(t)\right]^{\beta}}{\sum_{m=1}^{a_i}\left[\tau_{im}(t)\right]^{\alpha}\left[\eta_{im}(t)\right]^{\beta}} \qquad (13)$$

where τ_{ij} and η_{ij} are the pheromone intensity and the heuristic information between station i and bus j , respectively. α is the relative importance of the trail and β is the relative importance of the heuristic information η_{ij}. The problem specific heuristic information

$$\eta_{ij}=Zone_{ij} \qquad (14)$$

where $Zone_{ij}$ represents the zone of station i at bus j .

$$Zone_{ij}=\begin{cases}1 & if\ bus\ j\ within\ zone\ i\\ 0 & otherwise\end{cases}$$

B. Global Updating Rule

During the construction process, no guarantee is given that an ant will construct a feasible solution which obeys the reliability constraint. The unfeasibility of solutions is treated in the pheromone update: the amount of pheromone deposited by an ant is set to a high value if the generated solution is feasible and to a low value if it is infeasible. These values are dependent of the solution quality. Infeasibilities can then be handled by assigning penalties proportional to the amount of reliability violations. In the case of feasible solutions, an additional penalty proportional to the obtained solution is introduced to improve its quality.

Following the above remarks, the trail intensity is updated as follows:

$$\tau(t) = (1-\rho)\cdot\tau(t-1) + \Delta\tau \qquad (15)$$

where ρ is a coefficient such that $(1-\rho)$ represents the evaporation of trail and $\Delta\tau$ is updated trail and can be expressed as:

$$\Delta\tau = \Delta\tau_{ij}^{k} \qquad (16)$$

where k is number of ants and *i,j* is station i at bus j and $\Delta\tau_{ij}^{k}$ is given by:

$$\Delta\tau_{ij}^{k} = \begin{cases} 1 & \text{if } k^{th} \text{ ant chooses path} \\ 0 & \text{otherwise} \end{cases} \qquad (17)$$

V. NUMERICAL EXAMPLE

The simulation results shown in this paper are simulated by using MATLAB program on a Core2 duo, 1.8 GHz 1GB RAM personal computer. The ACO is tested to 100 runs for solving the optimal location fast charging problem.

A. *ACO Parameter and Computation*

The parameter of ACO is set as follows

- Number of ant = 20
- Maximum iteration = 100
- α =1, β = 0.8, ρ =0.05

B. *Test System and Parameters*

The power distribution system covering 10.5 square kilometers in a Tianjin Development Zone illustrated in Fig. 7 is used to test the proposed method. The system data and parameters include thirty thousand/ km^2 of the population density, one hundred thousand of which 30% is electric vehicles of the car ownership. The location of gravity center and the number for each small area can be found in [11]. There are 3,140 electric vehicles in the Development Zone. the number of charging station can be obtained from equation (1). The capacity of each fast charging station is 500 kVA. Parameters of traffic flow and EV FCS are summarized in Table III.

The distribution networks used in this example are the modified IEEE 69-bus test systems divided into 6 zones illustrated in Fig. 6. System data and parameters are shown in Table I and II. The 69-bus system has 68 sections with the total customer load of 4.014 MW and 2.845 MVar. It has 12.8 kV base and line loading of distribution is 10 MVA. This total customer load is set as peak demand on the weekday. The location of each bus in Tianjin Development Zone can be found in Fig. 8. The original numbers of total real and reactive power losses of the system are 250.47 kW and 112.58 kVar, respectively. The maximum and minimum voltages are 1.0 p.u. and 0.9 p.u. respectively.

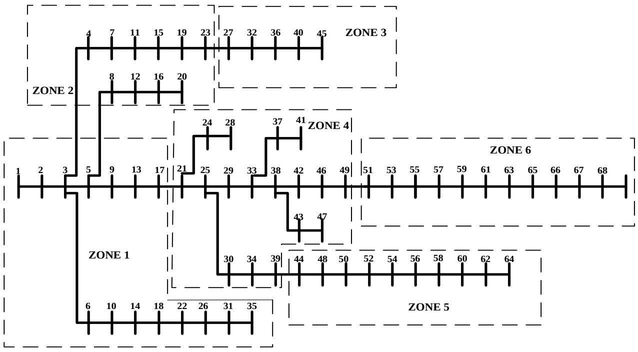

Fig. 6. The Modified 69-bus test system about 6 zones

Fig. 7. Tianjin development zone

TABLE I. BUS NUMBER IN EACH ZONE

Zone	Bus
1	1,2,5,6,9,10,13,14,17,18,22,26,31,35
2	4,7,8,11,12,15,16,19,20,23
3	27,32,36,40,45
4	21,24,25,28,29,30,33,34,37,38,39,41,42,43,46,47,49,51,53
5	44,48,50,52,54,56,58,60,62,64
6	55,57,59,61,63,65,66,67,68,69

C. *Results and Discussions*

The ACO algorithm is used to obtain best location of dc fast charging station on distribution power system considering traffic constraint of FCS on residential distribution grid while maintaining power system security. The best result is shown in Table Ⅳ and Fig. 8.

The solution quality of ACO is shown in Table Ⅴ.

Fig. 8 shows the optimal location of EV charging station connected on the power distribution system.

The location obtained proposed method give lowest total cost and the installed dc fast charging still maintain voltage and line loading in range of limit in power distribution system. EV charging station will serve all load points which represent population of electric vehicles. Form the result, ACO can find optimal location of fast charging station which serves all cars to recharge its battery every day. The solution quality of result is shown in Table Ⅴ. The minimum of standard deviation value show that ACO have effectiveness to solve this problem.

TABLE II: SYSTEM DATA OF MODIFIED IEEE 69 BUS TEST SYSTEM

From Bus	**To Bus**	**R (p.u.)**	**X (p.u.)**	**Bus No.**	***Pload MW***	***Qload MW***
1	2	0.0000205	0.0000632	1	0	0
2	3	0.0000305	0.0000732	2	0	0
3	5	0.0000916	0.0002197	3	0	0
3	6	0.0002686	0.0006592	4	0	0
3	4	0.0002686	0.0006592	5	0	0
4	7	0.0039063	0.009552	6	0.026	0.0186
5	9	0.001532	0.0017944	7	0.026	0.0186
5	8	0.0002075	0.0005127	8	0	0
6	10	0.0039063	0.009552	9	0	0
7	11	0.006427	0.0075073	10	0.026	0.0186
8	12	0.0051941	0.0127136	11	0	0
9	13	0.0223389	0.011377	12	0.079	0.0564
10	14	0.0242798	0.0080261	13	0.0026	0.0022
11	15	0.0018555	0.0021667	14	0	0
12	16	0.017688	0.04328	15	0.024	0.017
13	17	0.0232605	0.0118469	16	0.3847	0.2745
14	18	0.0042847	0.001416	17	0.0404	0.03
15	19	0.0001099	0.0001282	18	0	0
16	20	0.0050171	0.0122742	19	0.024	0.017
17	21	0.0056274	0.0028687	20	0.3847	0.2745
18	22	0.0214233	0.0070801	21	0.075	0.054
19	23	0.0444519	0.0519348	22	0	0
21	25	0.003009	0.001532	23	0.0012	0.001
21	24	0.0056641	0.002887	24	0.0405	0.0283
22	26	0.0512085	0.0171875	25	0.03	0.022
23	27	0.0189209	0.022113	26	0.014	0.01
24	28	0.0202576	0.0067993	27	0	0
25	29	0.0499878	0.0165222	28	0.0036	0.0027
25	30	0.0106201	0.0054077	29	0.028	0.019
26	31	0.104248	0.0344604	30	0.0044	0.0035
27	32	0.0025024	0.0029175	31	0.0195	0.014
29	33	0.0114258	0.0037781	32	0.006	0.0043
30	34	0.0123901	0.006311	33	0.145	0.104
31	35	0.0899658	0.0297424	34	0.0264	0.019
32	36	0.0005615	0.000708	35	0.006	0.004
33	38	0.0434204	0.0143494	36	0	0
33	37	0.0122803	0.0037292	37	0.018	0.013
34	39	0.0173462	0.0088318	38	0.145	0.104
36	40	0.0066467	0.0083801	39	0.024	0.0172
37	41	0.0002869	0.0000854	40	0.0392	0.0263
38	42	0.0628662	0.020752	41	0.018	0.013
38	43	0.0451294	0.014917	42	0.008	0.005
39	44	0.0171692	0.0087463	43	0.028	0.02
40	45	0.0000549	0.0000732	44	0	0
42	46	0.0637207	0.0210571	45	0.0392	0.0263
43	47	0.0002869	0.0000977	46	0.008	0.0055
44	48	0.0970459	0.0325745	47	0.028	0.02
46	49	0.0645752	0.0213379	48	0	0
48	50	0.048053	0.0160522	49	0	0
49	51	0.0119995	0.0039673	50	0	0
50	52	0.0185669	0.0061401	51	0.0455	0.03
51	53	0.0228516	0.0075562	52	0.1	0.072
52	54	0.0235657	0.0071533	53	0.06	0.035
53	55	0.0002869	0.0000977	54	0	0
54	56	0.0309753	0.0157776	55	0.06	0.035
55	57	0.0199951	0.0066101	56	1.244	0.888
56	58	0.0059448	0.0030273	57	0	0
57	59	0.012854	0.0042114	58	0.032	0.023
58	60	0.0088501	0.0045044	59	0.001	0
59	61	0.0208496	0.0068909	60	0	0
60	62	0.0433655	0.0220886	61	0.114	0.081
61	63	0.0008545	0.0002808	62	0.227	0.162
62	64	0.0635376	0.0323608	63	0.005	0.0035
63	65	0.0097107	0.0032104	64	0.059	0.042
65	66	0.0211365	0.0069885	65	0.059	0.042
66	67	0.0457031	0.0151062	66	0.059	0.042
67	68	0.0457031	0.0151062	67	0.059	0.042
68	69	0.0457031	0.0151062	68	0.059	0.042
				69	0.059	0.042

VI. CONCLUSION

This paper presents ACO algorithm which is employed to search best location of DC fast charging station on the power distribution system considering traffic constraint of FCS while maintaining power system security of residential distribution system. The traffic flow of EVs is considered as a major factor in which EVs travel from load point into EVs fast charging station connected to power distribution system buses. The simulation result demonstrates that EVs charging station in the optimum location has minimum total cost and real power loss. In addition, the results indicate that ACO algorithm has robustness and effectiveness to search optimal location of fast charging station connected on a power distribution system.

TABLE III. PARAMETER OF TRAFFIC FLOW AND EV CHARGING STATION

Name	**Parameter**	**Unit**
Initial investment(F)	10,000,000	Yuan
Load factor of charging station(lf)	0.95	
Load factor of EV car (lfv)	0.5	
Service time of EV charging station(o)	18	Hour
charging time of each vehicle(chg_time)	0.25	Hour
Charging station capacity(Cap)	500	kVA
Power factor($\cos\varphi$)	1	
Capital recovery period(m)	20	Year
Discount rate(k)	0.1	
Conversion coefficient(α)	1.2	
Road twist coefficient(t)	1.1	
Turnaround coefficient(z)	1.5	
Smooth traffic coefficient (η)	1.1	
Loss coefficient(L)	1.3	
Annual charging times per vehicle(c)	180	
Simultaneity factor(f_1)	0.95	
Demand factor(f_2)	0.95	
Charging efficiency(q)	0.9	
Charging radius(R)	1.2	km

TABLE Ⅳ. BEST LOCATION OF EV STATION

Item	**Location(Bus)**
Charging station 1	13
Charging station 2	11
Charging station 3	36
Charging station 4	46
Charging station 5	56
Charging station 6	66
Total cost	85,795,700 Yuan
Power Loss	346.85 kW

TABLE Ⅴ.SOLUTION QUALITY OF ACO

Item	**Value(**Yuan**)**
Maximum cost	86,070,500
Average cost	85,834,200
Minimum cost	85,795,700
Standard deviation	24,210

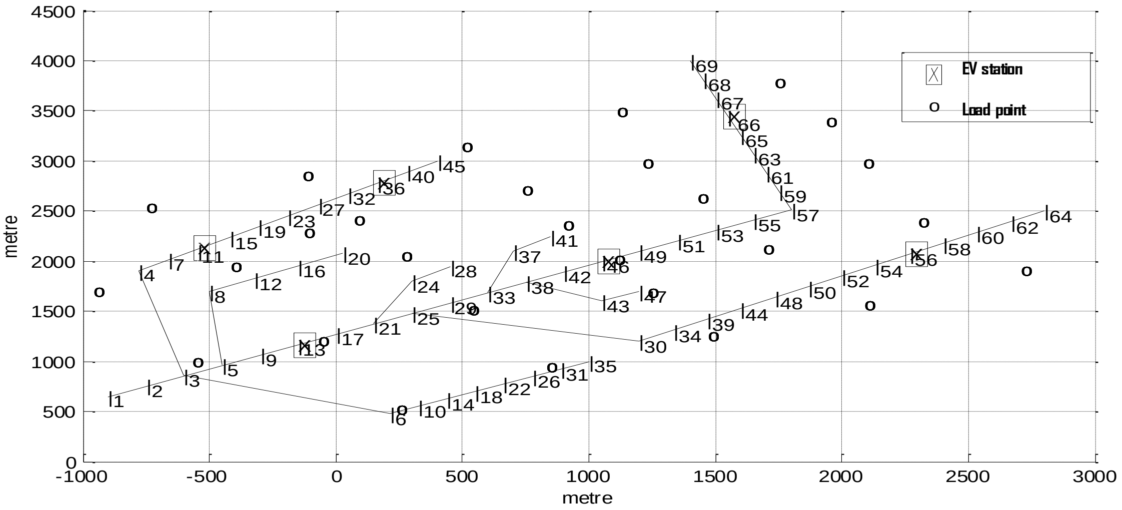

Fig. 8. Best location of EV fast charging station in a distribution system with load point of traffic

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Prakornchai Phonrattanasak was born in 1974 and received his B.Eng. and M.Eng. both in Engineering from Khonkaen university, Thailand in 1996 and 2002 respectively. He became a member of IACSIT in 2012. Currently, he is a lecturer at North Eastern University, Khonkaen, Thailand while pursuing his PhD in Engineering at the Department of Electrical and Computer Engineering, Thammasat university. His research interests are in the area of power system economics, optimization modelling, renewable energy and smart grid development issues.

Nopporn Leeprechanon was born in 1969 and obtained his B.Eng.(Hons) and M.Eng., both in Electrical Power Engineering from the King Mongkut Institute of Technology Ladkrabang, Thailand in 1991 and 1996 respectively, and received his PhD from Royal Melbourne Institute of Technology (RMIT University), Australia in 2003. He experienced in the power industries for several years before joining Thammasat University in 1996, He is currently an Assistant Professor within the Department of Electrical and Computer Engineering, Thammasat University. His research interests are in the area of power system economics, optimization modelling, power system planning, pricing and energy policy issues including smart grid and renewable energy development.