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Locating Fast Charging Stations for Plug-In Hybrid Electric Vehicles in Distribution Networks with Considering Load Uncertainties Using a New Multi-Agent Harmony Search Algorithm

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Abstract

The use of Plug-in Hybrid Electric Vehicles (PHEV) can be known as an efficient factor for reducing the pollution caused by fossil fuels. It is obvious that with increasing the number of these vehicles, charging stations are needed to be established on the network. Therefore, in this paper, the problem of locating fast charging stations for Plug-in Hybrid Electric Vehicles using a new Multi-agent Harmony Search Algorithm is completely studied. According to the fact that the load uncertainties caused by charging hybrid electric vehicles are an effective and important factor to determine the number and also suitable locations of charging stations, the Poison and normal distributions are here used for considering uncertainties about the number of hybrid electric vehicles per hour and the charging demand for each hybrid electric vehicle, respectively. To study the problem in this paper, first, 10,000 different scenarios are made per hour and then, using Latin Hypercube, the number of the scenarios of each hour is dropped to 10. Finally, a new Multi-Agent Harmony Search Algorithm is applied to reduce network losses in different scenarios. The obtained results show that determining the number and the suitable locations for vehicle charging stations can greatly reduce the risk of overloading in the network caused by charging hybrid electric vehicles.

Keywords: Plug-in Hybrid Electric Vehicles, Poison and Normal Distributions, New Multi-Agent Harmony Search Algorithm, Charging Stations.

1. INTRODUCTION

Today, one of the main problems in the field of air pollution is global warming. Various studies have shown that the transportation part is an important factor in air pollution, so researchers have begun a lot of research in this area. Electric vehicles (EVs) are important innovations that are considered to

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be the best options for combating air pollution and also have lower maintenance and operating costs and low noise emission [1]. They are also a good option to meet the growing demand for fossil fuels, but increasing the number of EVs is a major threat to the power grid, and increasing the demand for electricity to charge EVs may hamper the smooth operation of the power grid. Ensuring the secure and steady performance of the distribution network, analyzing the impact of EV charging stations on the power grid is essential. Reference [2] provides an overview of articles on the influence of EV charging stations on the power distribution network.

Another important factor for the overall development of the EV industry is the rational planning of EV charging stations. In [3], considering the charging capacity constraints and investment limitation, the optimal charging station planning model for EVs with the objective function minimizing annual cost is presented. In this paper, first, the constraint of service radius is replaced with the constraint of battery capacity to be the EV factor to eliminate possible planning damage and then, the proposed model is solved using the chaos and harmonic search algorithm and finally, the optimal result for the charging station planning is obtained.

On the other hand, EVs need to recharge their batteries after traveling a definite distance. Therefore, the widespread deployment of EVs requires the development of stable infrastructures for charging. Finding the placement of charging stations is a complex optimization problem involving some decision variables, objective functions and constraints. Also, it can be categorized as a non-convex and non-combinational problem including transport and distribution networks. The complex and nonlinear nature of this problem has forced researchers to carry out meta-heuristic optimization algorithms for solving it. In [4], meta-heuristic algorithms used to solve charging station problem, are studied to present their main features, advantages and disadvantages.

Reference [5], a review paper, describes the types of charging technologies studied in the articles for EVs in terms of their converter topologies, power levels, power flow directions, charging control strategies and implemented practical applications. Also, in this article with the aim of increasing the life of the cell cycle and maintaining the high charging efficiency for lithium ions batteries, the optimal charging size of these batteries is estimated using genetic algorithm.

Reference [6] focuses on the development of EVs in the UK in spite of giving a brief introduction about the global landscape of EVs and their infrastructures. In this article, three main factors which are necessary to be considered in a typical site, including design, location, and cost are studied in details.

In [7], the optimal charging plan for EVs under dynamic pricing plans is briefly examined and a detailed comparison is made between Real Time Pricing (RTP), Time of Use (ToU), Critical Peak Pricing(CPP) and Peak Time Rebates (PTR). It concludes that RTP scheme is more promising than other types because it has more flexibility for the customers of EVs to regulate their requests, but involves a higher degree for bill instability which may affect the customer’s sureness.

In [8], a modified capacitive current refueling location model based on sub paths (CFRLM_SP) is used for obvious recording time-varying PEV charging demand in the transport network under driving range constraints. In this paper, first, the additional limitations of CFRLM_SP to increase model accuracy and computational efficiency is examined and then, a stochastic complex second-order cone programming model is proposed for the planning of fast charging stations for PEV. This model considers the constraints belonging to the CFRLM_SP of transport network and AC power flow network. Finally, Numerical experiments have been performed to demonstrate the efficiency of the proposed method.

In [1], All the researches related to EV charging stations until 2019 have been reviewed. In this paper, it is tried to comprehensively review the recent developments for the planning of EV charging infrastructures and briefly discuss various mathematical models and algorithms for sketching an EV charging station.

In [9], a tool is proposed and developed to identify the possibility of charging along a path through simulating the journey by an electric vehicle and evaluating the charging station plans on the same path.

In [10], a new practical approach is introduced for the optimal allocation of charging stations for electric vehicles (EV) in large-scale transport networks. Due to the limited driving range of these vehicles, it is necessary to provide accessible charging stations for EV owners to drop their stress. The purpose of Route Node Coverage (RNC) problem, in this paper, is to find the minimum number of charging stations and also their locations in order to support the possible routes available for a transport network.

The presence of hybrid EVs in distribution networks has created a new need, the construction of charging stations, to be considered in planning electrical distribution systems.

In [11], fast charging stations are to minimize the cost of investment and charging while in [12] charging stations are located for the aim of minimizing their installation cost. In [13] the locations of charging stations are found for the aim of maximizing social welfare by minimizing the costs of charging, power generation and construction of stations. In fact, this paper has examined the issue in the electricity market. In [14], locating and determining the optimal size of charging stations are conducted with the aim of minimizing the cost of investment, operation and maintenance of charging stations and network losses. In this paper, first the optimal locations for charging stations with considering the service radius of charging stations are specified using a two-stage screening method. Then, the optimal capacity of charging stations with considering the costs associated with charging stations is specified using a modified primal- dual interior point algorithm.

In [15], the problem of finding the locations for fast charging stations is studied with the aim of minimizing installation costs and losses of the distribution network. In [16] fast charging stations are compared with battery replacement stations. In this work, location and the optimal size of fast-charging stations and battery replacement stations are specified using modified Differential

Evolution Algorithm. This algorithm, as its name implies, lies in the category of evolutionary algorithms (EAs). This paper finally reaches the fact that fast charging stations create sharp peaks in the load curve and lead to more investment in transformers and lines. In contrast, battery replacement stations can make the load profile flatter due to the fact that the batteries would be charged at night.

In [17], determining the proper location capacities for fast charging stations is formulated as a Mixed-Integer Non-Linear Problem (MINLP) and solved using Genetic Algorithm. In this article the objective function is to minimize the investment costs of fast charging stations and energy losses.

In [18], the problem of finding the locations of fast charging stations is solved from the view point of a social planner. The objective function is here to minimize the costs of investment, maintenance, repairing, buying energy and customer stop times. Particle Swarm Optimization Algorithm is here used for determining the locations and optimal sizes of fast charging stations.

In [19], the problem of distribution network development planning with regard to electric vehicle charging systems is addressed. In this paper, the planning is static and the decision variables include determining the locations and sizes of the above distribution substations, feeders and charging systems for electric vehicles.

In [20], it has been shown that simultaneous planning of distribution network and PHEV charging systems can significantly cause reducing the investment. In this reference from a new multi-objective evolutionary algorithm called decomposition based multi-objective evolution algorithm is used for Non-dominated solutions.

In [21], planning the distribution network development and charging systems are dynamically conducted. In the proposed model, location, size and optimal times for constructing substations, feeders and parking for PHEVs are determined. In this paper, Non-dominated Sorting Genetic Algorithm is used to solve the problem. After achieving Pareto optimal non-dominated solution set, a fuzzy method is used to select the best solution. One of the most important advantages of dynamic programming in the presence of electric vehicle charging systems is the possibility of considering different scenarios as well as different uncertainties related to vehicles. With considering uncertainties such as vehicle penetration factor, it is possible to plan the development of distribution network and charging systems for electric vehicles with more appropriate investment.

The problem related to different uncertainties in the presence of PHEV charging systems is addressed in [22]. The uncertainties that this reference addresses, are: the penetration factor of electric vehicles, the success or failure of coordinated charging of electric vehicles. In this paper, different scenarios and their corresponding probabilities are considered for each of these cases, and distribution network development planning is done for each of these scenarios. The planning is done statically and the problem is solved using a genetic algorithm.

In [23], planning in fast charging stations and scattered productions is simultaneously and statically done. To solve the problem, genetic algorithm is used with the objective function including investment cost, reliability, losses, voltage profile and environmental issues. It is, in this paper, concluded that planning simultaneously in charging stations and scattered productions lead to better results rather than planning in charging stations without considering scattered productions.

In [24], the well-known types of Harmony Search Algorithm are presented with their applications and also their strengths and weaknesses are expressed.

In [25], the potential of using Harmony Search Algorithm is examined in three countries including China, South Korea and Japan and also, the various applications have been demonstrated in various sciences such as mathematics, computer, electronic, mechanical, chemistry, civil and industrial engineering.

The review article referred in [26] focuses on the historical development of Harmony Search Algorithm instead of its applications.

In [27], in addition to a detailed study on the basic concept of Harmony Search Algorithm and its types, the innovative applications of that are analyzed and summarized in the field of intelligent manufacturing.

As mentioned in [28], Harmony Search Algorithm is used in power systems to solve the problems such as the high cost of MG microgrids, the balance between supply and demand, and so on.

In [29], UC model is formulated with EV, which includes the constraints of force balance, rotational storage, minimum climb time, production, and EV.

The Improved Harmony Search Algorithm mentioned in [30] and [31] has been respectively used to solve the problems of optimal positioning and sizing to use the benefits of reactive power compensation and distribution network planning.

A multi-agent system consists of a set of independent software agents. Each agent discovers its knowledge from the environment and other agents to be able to help obtaining optimal goals, and collaborates and competes with other agents [32]. In fact, a multi-agent system is a network structure composed of scattered physical or logical agents, which perform complex tasks through negotiation and coordination [33].

Some papers have suggested optimizing using Particle Swarm Optimization Algorithm in combination with multi-agent system [34-37]. In this approach, a more dynamic tool is obtained by giving more independence and superior learning capability to the particles and asynchronous execution [38].

In [35], Multi-Agent Particle Swarm Optimization (MAPSO) is used to solve the problem of optimal design of grid-connected PBES. Kumar et al. used MAPSO to solve economic load distribution problem to be a nonlinear constrained optimization problem [39]. Zhao et al. used MAPSO to optimize reactive power distribution and have validated this method by an IEEE 30-bus power system [40].

The main purpose of this paper is to determine the optimal locations for fast charging stations in distribution networks. Due to the random nature of the loads generated by EVs, the chosen locations should be such that the operation of the network is not disrupted.

2. PROBLEM FORMULATION

The objective function introduced in Eq. (1) is defined to reduce network losses and investment costs for the station construction. PHEVs can be charged on the network during the day. Each charging station is modeled on the network such as an electrical load. The location and amount of load per hour have a great impact on network losses.

$$\begin{aligned} &obj\colon min\{f = C_{loss} + C_{INV}\} \\ &C_{loss} = \sum_{d=1}^{N_d} \sum_{t=1}^{24} \rho_e^{t,d}\ E_{loss}^{t,d} \\ &C_{INV} = \sum_{i \in N_{st}} \rho_{st}\ cap_{st}^{i} \\ &E_{loss}^{t} = 10^{-6} \sum_{i,j \in line} R_{ij} \times \left|I_{ij}^{t}\right|^2 \end{aligned} \tag{1}$$

In the equation, N_d is equal to 12. Considering the fact that the study of whole days of a year is time-consuming, one day is chosen for each month as indicator, i.e. the results of that day are generalized to the whole days of that month.

3. PROBLEM CONSTRAINTS

- equality constraints of AC load flow

Actually, these constraints including active and reactive power injection constraints from each bus to the network, can lead to load flow equality in the network.

If the constraints are satisfied, this is ensured that the solution found for the problem can be used in the network.

$$\begin{aligned} P_{Gi} - P_{Li} &= \sum_{i=1}^{n-bus} V_i V_j \big(G_{ij} cos\theta_{ij} + B_{ij} sin\theta_{ij}\big) \\ Q_{Gi} - Q_{Li} &= \sum_{i=1}^{n-bus} V_i V_j \big(G_{ij} cos\theta_{ij} + B_{ij} sin\theta_{ij}\big) \end{aligned} \tag{2}$$

- AC power line constraint

Since the structure of each line causes a constraint on the power passed from that line, the power must be limited to a certain amount. This constraint can be defined using the following equation.

$$\begin{aligned} &\left|F_{ij}\right| \le F_{ij}^{max} \\ &F_{ij} = V_{ij}.I_{ij} \end{aligned} \tag{3}$$

- Voltage constraints

In the operation instruction of any network, lower and upper limits are determined for the voltage of that network as follows:

$$V^{\min} < |V_i| < V^{\max} \tag{4}$$

- Minimum network load factor constraint

Network load factor is an important indicator for the load changes occurred during 24 hours. Therefore, the network load factor must exceed a minimum certain amount shown in Eq. (5).

$$\begin{aligned} &LF \ge LF_{min} \\ &LF = \frac{PD_{AVG}^{t}}{PD_{max}^{t}} \end{aligned} \tag{5}$$

4. UNCERTAINTIES ABOUT CHARGING PLUG-IN HYBRID ELECTRIC VEHICLES

In the studied problem, uncertainties can be divided into two following main parts:

The first part: Uncertainty about the number of vehicles entering the charging station per hour

And the second part: Uncertainty about the time it takes to charge each vehicle.

4.1. Uncertainty About the Number of Vehicles Entering the Charging Station Per Hour

During day and night, the number of PHEVs entering fast charging stations to be charged, depends on two factors below:

1. what time is now and at this time, how many vehicles are coming to the station?
2. how much charging each vehicle needs and how long that vehicle stops at the charging station to be charged?

For the first factor, Poisson probability distribution function can be used. It means that, the number of vehicles entering a charging station at any time of a day, is a random variable. The following equation shows Poisson probability density function for this part.

$$f = \frac{e^{-\lambda}\lambda^{k}}{k!} \tag{6}$$

4.2. Uncertainty About the Time Taking for each Vehicle to be Charged

The time taking for charging vehicles, depends on their battery capacity and the amount of charging they need. The maximum amount of the SOC of a vehicle battery is calculated using the distance traveled by that vehicle.

For the distance traveled by each vehicle, a normal probability distribution function is used as follows:

$$f = \frac{1}{\sqrt{2\pi\sigma}} e\left(-\frac{(x-\mu)^2}{\sigma}\right) \tag{7}$$

and the SOC of the battery of that vehicle can be calculated as follows:

$$SOC = \begin{cases} 0 & m > AER \\ \frac{AER - m}{AER} * 100\% & m \leq AER \end{cases} \tag{8}$$

AER is the distance that vehicles travel and is calculated by the probability distribution introduced in Eq. (7).

Now, PHEV charging time can be calculated using the following formula:

$$t_D = \frac{C_{bat}.(1 - SOC).DOD}{\eta.P} \tag{9}$$

5. DETERMINING DIFFERENT SCENARIOS FOR STUDIED PROBLEMS

To consider the uncertainty, different scenarios are needed to be defined. For this purpose, the following steps can be used to make different scenarios by available probability distribution functions.

In the first stage, n scenarios are made using the Poisson distribution to determine the number of vehicles in each station.

In the second stage, m scenarios are made using Normal distribution to determine the amount of charging required for each vehicle.

In the third stage, a comprehensive matrix involving $n \times m$ different modes is made by combining the previous matrices.

In the fourth stage, the scenarios are reduced to n_s using kmeans method. In each scenario, the number of vehicles in each station and the amount of the charging requested by every vehicle is determined by a distinct possibility. Finally, a general objective function is defined as the reduction of the mathematical expectation of the cost of losses and station constructions in the total studied scenarios. The following equation shows this fact.

$$obj: min\left\{\sum_{k=1}^{n_s} f_k pr_k\right\} \tag{10}$$

To understand the necessitate of the steps of solving the problem mentioned earlier, a flowchart is provided in Fig. 1.

6. DESCRIPTION OF THE PROPOSED MULTI-AGENT HARMONY SEARCH ALGORITHM

Now, the proposed Multi-Agent Harmony Search Algorithm is presented. The optimization algorithm begins by a random harmony memory composed of pieces called harmonies. Each harmony is considered an agent which stands in the search space. Agents are categorized into several groups. Each group is eventually a functional unit and its members participate in updating the harmony memory by competing with each other using pitch adjustment mechanism. The agents also have a detection tool. If the searching falls into a flat zone, the agents will change searching plan to jump out of the flat zone by contributing the global optimization. This mechanism will guarantee the efficiency of searching.

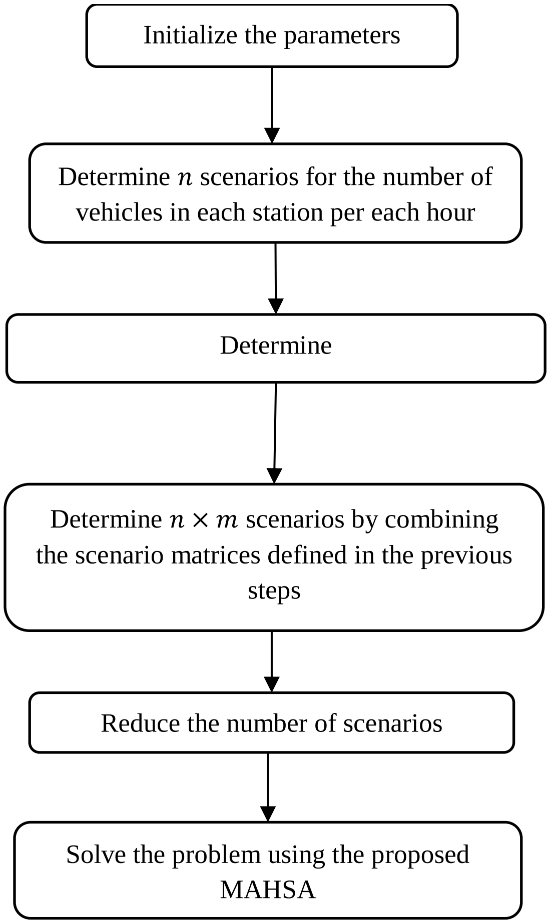


Fig. 1. Flowchart for solving problems.

7. CASE STUDIES

For the case study the distribution network of 24 bus RBTS BUS24 is studied. It is one of the most famous networks for the various fields of power. This network is completely introduced in [23]. Figure 2 shows the Single-line diagram of this network. As shown, this network has a super-distribution section and a distribution section. In the super-distribution part, the network has a radial arrangement, while it has a radial arrangement in distribution parts. The network has two voltage levels including 11 kV and 33 kV and also, it has 38 load supply points. In the current research, the peak load of the network is studied because this situation is the worst situation. the network has 6 power transmission transformer and 67 sections and a total of 4779 consumers are fed through the network. By modeling the network load at peak load, the network load distribution at peak load is calculated. A total of 100 scenarios for charging PHEVs per hour and 100 scenarios for the number of vehicles entering the stations per hour are made. For this purpose, a standard deviation of 0.2 and an average of 0.3 are considered for the required charge of PHEVs per hour.

Poison distribution with $\lambda = 3$ is also considered for the number of PHEVs entering the stations per hour. The proposed Multi-Agent Harmony Search Algorithm with 100 harmonies is used to solve the problem.

For example, figure 3 shows the number of vehicles entering each station for the first four scenarios. In this section, the maximum number of visited vehicles per hour is considered 10. It can be seen that the most PHEVs in this model have more gone to the station in the morning and evening. Figure 4 shows the amount pf charging required for PHEVs entering the station per hour for the first 4 scenarios.

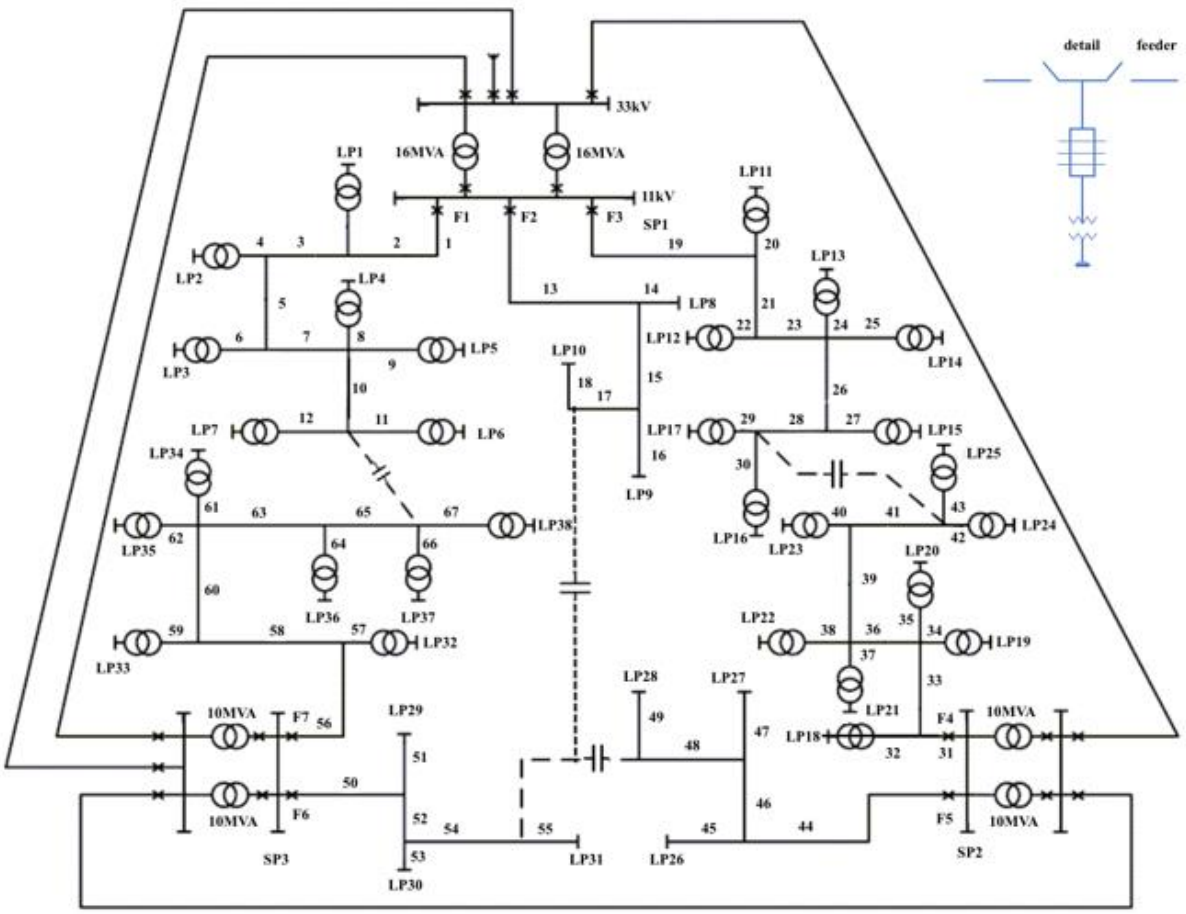
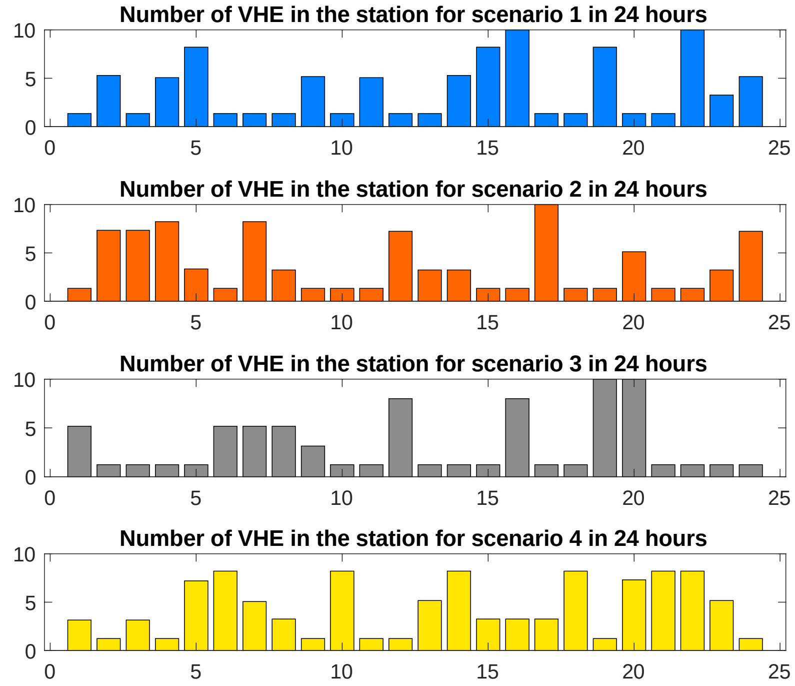


Fig. 2. Single-line diagram of studied network.

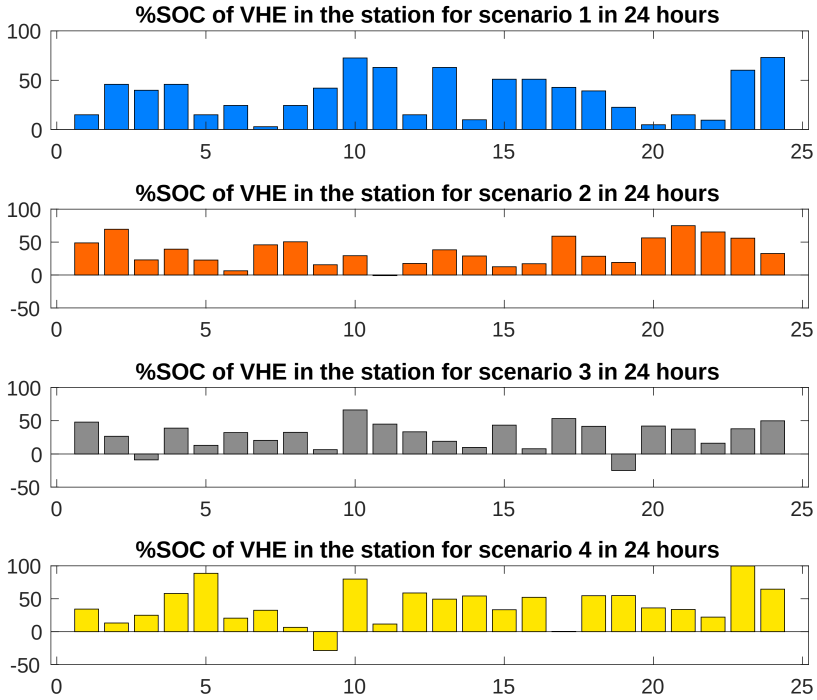

Number of VHE in the station for scenario 1 in 24 hours

Number of VHE in the station for scenario 2 in 24 hours

Number of VHE in the station for scenario 3 in 24 hours

Number of VHE in the station for scenario 4 in 24 hours

Fig. 3. Number of PHEV entering the station per hour for the first 4 scenarios.


%SOC of VHE in the station for scenario 1 in 24 hours

%SOC of VHE in the station for scenario 2 in 24 hours

%SOC of VHE in the station for scenario 3 in 24 hours

%SOC of VHE in the station for scenario 4 in 24 hours

Fig. 4. Amount of Charging required for 4 vehicles per hour in the first 4 scenarios.

The required amount of charging has been determined randomly for every hour. The combination of the scenarios mentioned earlier cause 10000 different scenarios, this number of scenarios is a huge number for analysis. Therefore, square minimum method is used to reduce it from ten thousand to 20. After analyzing the problem, 2 charging stations shown in Fig. 5, are located in the network.

Figures 6 and 7 show the network voltage at the time of the highest load required by the charging stations 1 and 2, respectively. In the scenarios, the maximum load required by stations does not occur at the same time. As it is seen, the voltage of points around the charging stations declines significantly but the voltage of other points of the network does not change. For decreasing the impact of charging stations on the network voltage, the reactive compensation equipment can be installed on the network at peak load hours. figures 8 and 9 show the loading on network lines when the charging stations 1 and 2 require a highest load, respectively.

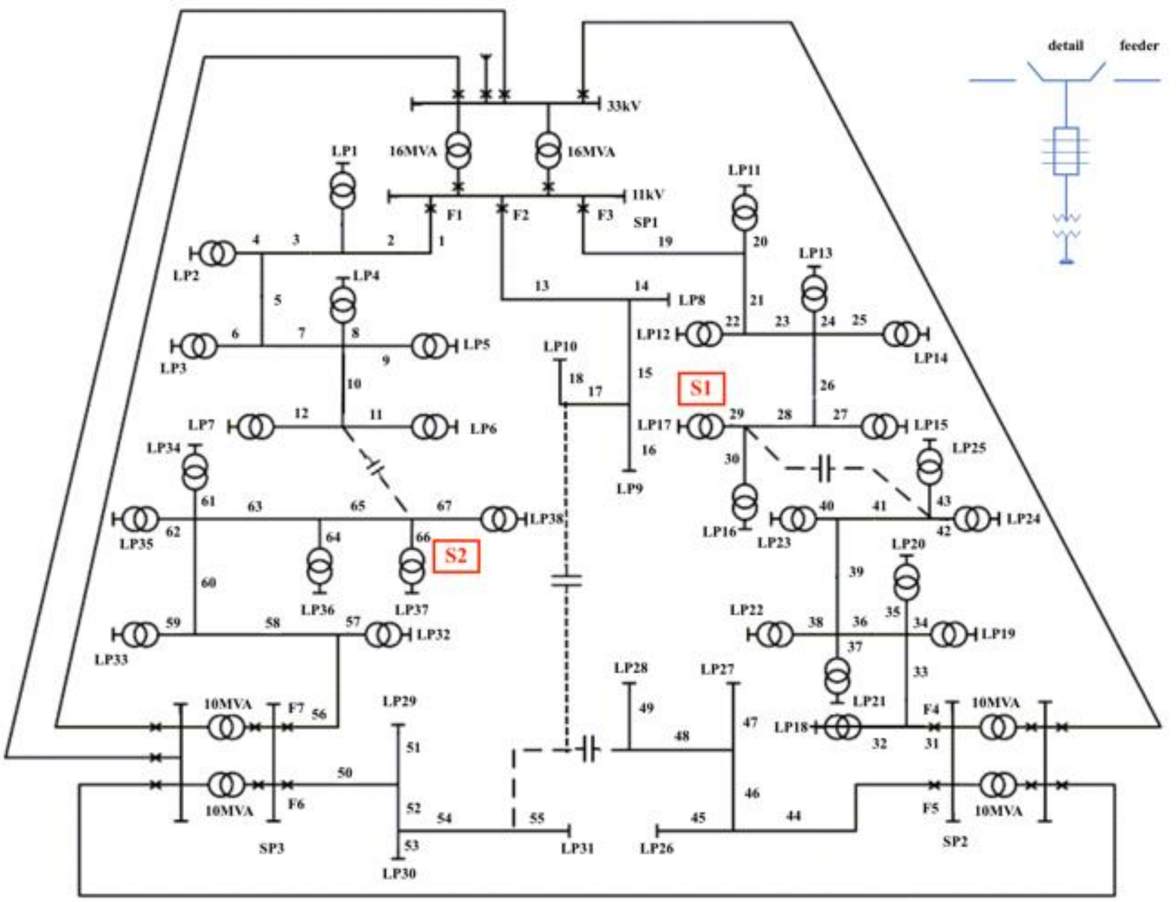


Fig. 5. Charging station locations.

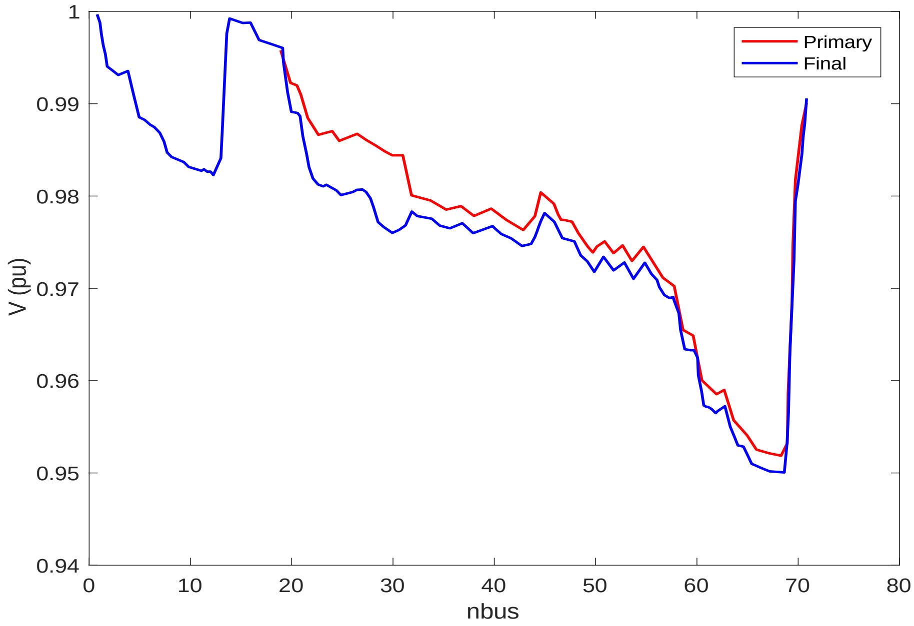


Fig. 6. network voltage before and after installing charging stations at the peak load time of station No. 1.

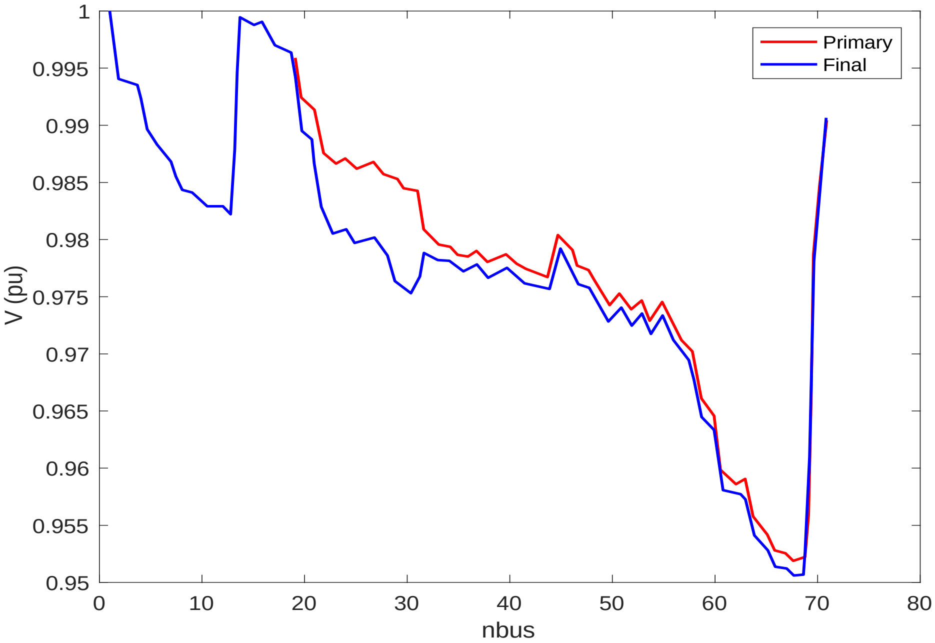


Fig. 7. Network voltage before and after installing charging stations at the peak load time of station No. 2.

In these figures, it is clear that the loading on network lines has increased in the installation locations of charging stations. However, due to the radial structure of the distribution network, the increase in load is also transmitted to the upstream parts of the network.

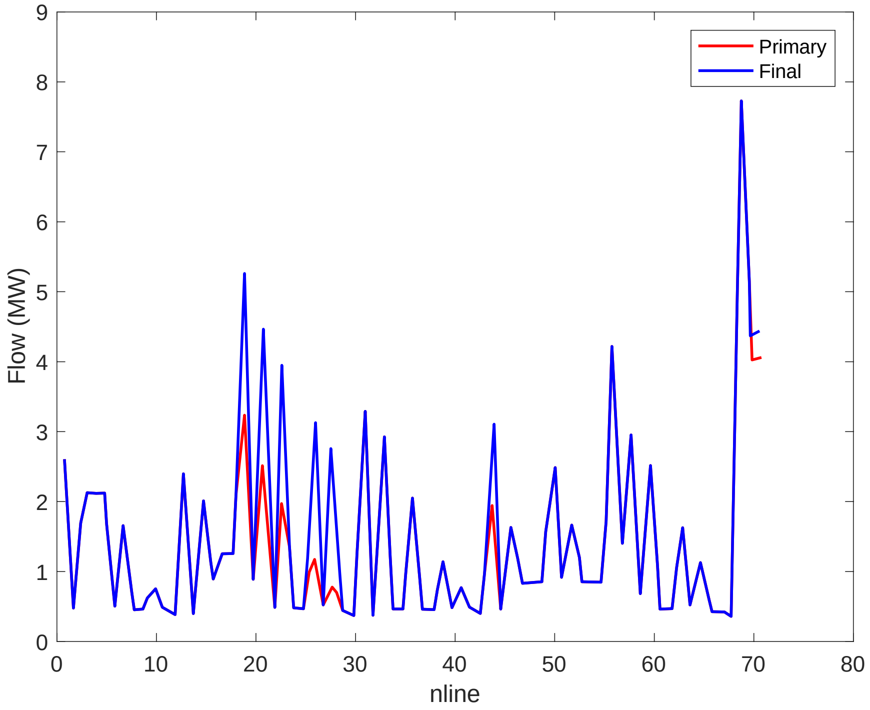


Fig. 8. Network lines loading before and after installing charging stations at the time of peak load of station No. 1.

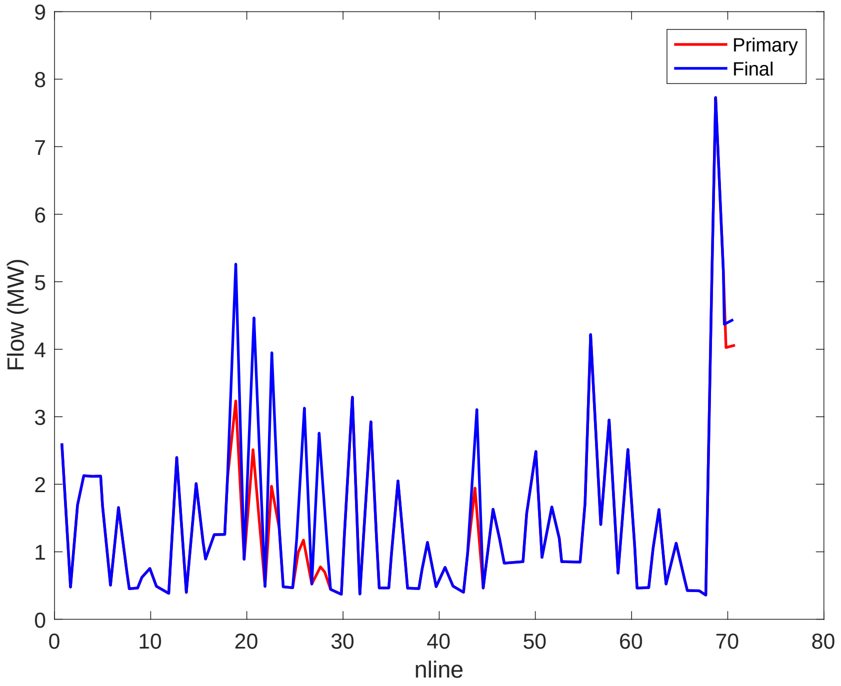


Fig. 9. network brunches loading before and after installing charging stations at the peak load time of station No. 2.

8. CONCLUSIONS

The main objective of this paper is to provide a method to determine the charging stations in network in a way that at the time of charging PHEVs, the overloading does not make problems in the network function. For solving this problem, a new Multi-Agent Harmony Search Algorithm is presented. The obtained numerical results show that if fast charging stations are established in not well places, they can make overloads in the network at peak hours due to high charging demands in these times. Therefore, the location of fast charging stations is very important and with locating them in optimal locations, network operators can simply management charging demands without any overload. It can be of course suggested that if PHEV charging station problem is defined by network reconfiguration problem, better results can be achieved.

NOMENCLATURE

B_{ij}	Imaginary part of the admittance of the line between the buses i and j (pu)
C_{bat}	Battery capacity
C_{INV}	Investment cost ($)
C_{loss}	Loss cost ($)
E_{loss}^{t}	Energy loss at time t (MWh)
F_{ij}	Apparent power line between the nodes i and j
G_{ij}	Real part of the admittance of the line between the buses i and j (pu)
I_{ij}^{t}	Electric current between the buses i and j at time t (A)
N_d	Number of studied days
n_s	Number of scenarios
N_{st}	Number of stations
P	Charging time
Q_{Gi}	Total reactive power generated in bus i (pu)
Q_{Li}	Total reactive power loaded on bus i (pu)
R_{ij}	Line resistance between the buses i and j (Ω)
V_i	Voltage of bus i (pu)
V^{max}	Upper limit for acceptable voltage range
V^{min}	Lower limit for acceptable voltage range
LF_{min}	Minimum load factor for the network
PD_{AVG}^{t}	average load in total studied days
PD_{max}^{t}	maximum load in total studied days
PG_i	Total active power generated in bus i (pu)
PL_i	Total active power loaded on bus i (pu)
pr_k	Probability of scenario k
DOD	Maximum discharge capacity rate
cap_{st}^{i}	The ith station capacity (MWh)
η	Charging efficiency
$\rho_{e}^{t,d}$	Power cost rate at hour t and day d ($/MWh)
ρ_{st}	Station construction cost rate ($/MWh)

θ_{ij}	Admittance angle of the line between the buses i and j (rad)

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