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Stochastic model for electric vehicle charging station integrated with wind energy

Hasan Mehrjerdi[a], Reza Hemmati[b,*]

[a] Electrical Engineering Department, Qatar University, Doha, Qatar
[b] Department of Electrical Engineering, Kermanshah University of Technology, Kermanshah, Iran

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ABSTRACT

This paper designs optimal charging facility and capacity for electric vehicle charging station. The charging facility is modeled containing fast, intermediate, and slow speed chargers. The nominal powers of these chargers are determined. The charging station is linked to the utility grid and it is supplied by wind energy and the energy storage devices. The optimal sizing and operation of storage system are optimized. The electrical grid is strengthened by line reinforcement. The uncertainty of wind power is included and dealt by stochastic programming. The model is expressed as stochastic mixed integer linear programming and solved by GAMS toolbox. The results demonstrate that the rated powers of quick, intermediate, and slow speed chargers are optimized on 116, 84, and 52 kW, respectively. The power of quick charger is 27% more than the intermediate one and the intermediate charger needs about 38% larger power facility compared to the slow speed system. The storage system is designed with rated power equal to 133 kW and it can discharge 85% of its energy during one hour. The lines are reinforced by 183% to supply the energy demand of the charging station. The energy, network reinforcement, and charging facility cover about 70%, 15%, and 12% of total cost. The network without storage system needs about 2% more reinforcement. Reduction of line reinforcement by 30% increases the battery power about 4 times.

Introduction

Together with development of renewable energies and electric vehicles rather than fuel powered vehicles, the optimal sizing and siting of electric vehicle charging stations become an issue in the electrical networks [1]. One of the recent topics is to equip the electric vehicle charging stations with renewable energy resources. Integration of renewable energy resources in electric vehicle charging stations is a useful and interesting problem that has attracted attentions in the recent years. In this regard, solar [1], wind, and hybrid wind-solar powered charging stations have been studied and realized [2]. In the most cases, electric vehicle charging station is linked to the distribution network and can supply its energy from both grid and renewable resources [3]. The electric vehicles are also integrated to the buildings [4].

Both the residential charging stations [5] and public charging stations can be supplied by renewable resources. The charging station must comprise adequate capacity and charging facilities to satisfy demands [6,7]. As well, location of the station is an important item that makes impacts on its utilization and operation. The electric vehicle charging stations may be supplied by micro-girds or the utility grid [8]. They make significant impacts on the electric grid in terms of voltage profile [9], power losses [10], harmonics [11] and the other electrical parameters. In order to deal with such effects, the electric vehicle charging stations have to be designed and operated subject to security constraints of the utility grid. The operation of electric vehicles is very similar to the battery storage systems [12].

The electric vehicle charging stations may also be utilized to improve the network performance.

They may be operated to manage the electrical loads through demand response programs [13]. The peak shaving strategy is the other benefit of these vehicles on the grid [14].

The electric vehicle charging stations are future loads of the electrical grids and it is necessary to consider them in the expansion planning of the network [15]. These charging station needs high amount of power during some time periods and they are important and effective loads in the network expansion planning which must be considered [16]. However, optimal design and operation of plug-in-electric vehicles may reduce the expansion planning cost because of discharging ability of plug-in-electric vehicles [17,18].

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* Corresponding author at: Department of Electrical Engineering, Kermanshah University of Technology, P.O. Box: 6715685420, Kermanshah, Iran.
E-mail addresses: Hasan.mehrjerdi@qu.edu.qa (H. Mehrjerdi), r.hemmati@kut.ac.ir (R. Hemmati).

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Nomenclature

Indexes and sets

m, M	Index showing buses, Set including buses
n, N	Index showing buses, Set including buses
z, Z	Index showing charging facilities, Set including charging facilities
p, P	Index showing hours, Set including hours
l, L	Index showing scenarios, Set including scenarios
o, O	Index showing seasons, Set including seasons
q, Q	Index showing vehicles, Set including vehicles

Parameters and design variable

$f^{l,m,n,o,p}$	Flowed power through the network lines (p.u.)
$\Theta^{l,m,o,p}$	Voltage angle (Rad.)
$a^{m,n}$	Line admittance (p.u.)
$ff^{m,n}$	Capacity of line (p.u.)
$ld^{l,m,o,p}$	Load demand (p.u.)
$vd^{l,m,o,p}$	Charging station demand (p.u.)
$cb^{m,o,p}$	Charged power to the storage system (p.u.)
$db^{m,o,p}$	Discharged power from the storage system (p.u.)
$eb^{m,o,p}$	Energy stored inside the battery (p.u.)
ccb^{m}	Nominal power of storage device (p.u.)
eeb^{m}	Nominal energy of storage system (p.u.)
$ev^{l,m,o,p,q}$	Energy inside the electric vehicle (p.u.)
$cv_z^{l,m,o,p,q}$	Power of charging facility (p.u.)
$u_z^{l,m,o,p,q}$	Binary variable [0,1]
eev^{q}	Nominal power of vehicle (p.u.)
ccv_z	Nominal power of charging facility (p.u.)
$N_{ev}^{l,m,o,p}$	Vehicles number
C_{evcs}	Capacity of charging station
$R_r^{m,n}$	Line reinforcement coefficient
AC_{evcs}	Annualized planning cost ($/year)
$e_p^{o,p}$	Electricity price ($/p.u.)
pr^{l}	Probability of scenario
t^{o}	Number of days in the season
v_{erb}	Investment cost on battery capacity ($/p.u.)
v_{prb}	Investment cost on battery power ($/p.u.)
v_{cf}	Investment cost on power of charging facility ($/p.u.)
CC_{evcs}	Investment cost for constructing charging station ($)
$v^{m,n}$	Investment cost for new lines ($/length)
v_{wt}	Investment cost on wind generating system ($/p.u.)
Kcc	Converting the total cost to annual cost

The charging performance of electric vehicle chargers can be improved by application of the battery-assisted charging system. Such system includes AC to DC current inverter, DC to AC voltage converter, battery storage system and electric car charger. The differences of charging rates in winter and summer are measured and denoted. This assessment is carried out to determine the impacts of vehicle battery temperature on the charging rate. It is demonstrated that the charging level in summer is higher than winter. The battery-assisted charging system improves the operation of chargers [19]. The charging stations are often supported by renewable energies. The optimization problem may be conducted to maximize the application of renewable resources in transportation. The uncertainty of the transportation patterns may be dealt by Monte Carlo simulation. Such stochastic model can be solved by available packages like GAMS software. This model can also deal with uncertainties related to the power production in renewable sources [20].

The application of smart charging of electric vehicles in the Digby, Nova Scotia, has been studied. Such smart charging system aims to charge the electric vehicles by renewable energy and studies the ability of increasing load and consequently the export capacity. The required transportation energy and travel timing are denoted. The charging scenarios are studied together with data of the grid like wind power, power flows, and electricity load. The smart charging increases the renewable energy usage by 20% under 10% adoption rate of electric vehicles. The charging by local renewable resources is increased by 73% [21].

Highlights of the model

The key highlights of the given model can be listed as follows;

- The charging station is integrated with wind turbine, energy storage structure, and multi-level charging facility.
- The designated station is linked to the upstream electrical grid and the electrical network reinforcement is carried out together with charging station design.
- The multi-level charging facility includes slow, intermediate, and fast speed charging facilities and wellbeing of the drivers is measured and investigated.
- The uncertainty of wind energy and load is modeled and studied and Seasonal energy and loading profiles are considered.
- The problem is expressed by mixed integer linear programming and implemented in GAMS/CPLEX.

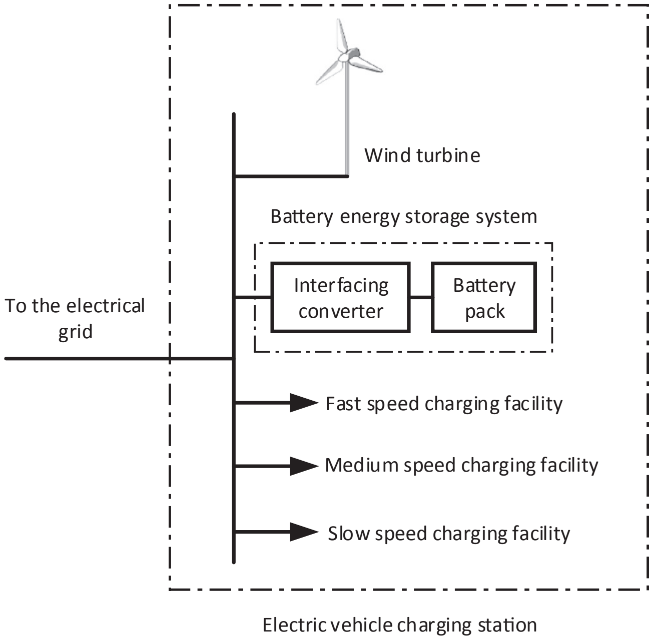

Fig. 1. Charging station connected to the electrical grid.

Design variables of the model

The proposed model optimizes the following variables;

- The charging time of electric vehicles
- The charging station capacity
- The harvested power from wind energy
- The rated power of multi-level charging facility
- The network reinforcement level
- The sizing and operation regime of energy storage system

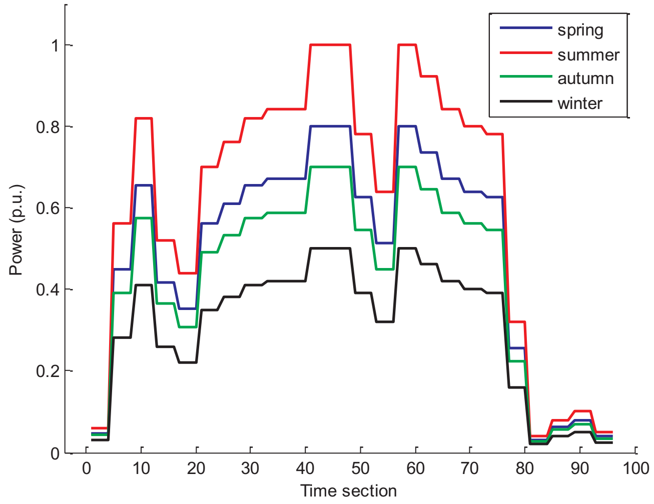

Fig. 2. Seasonal power profile of wind turbine.

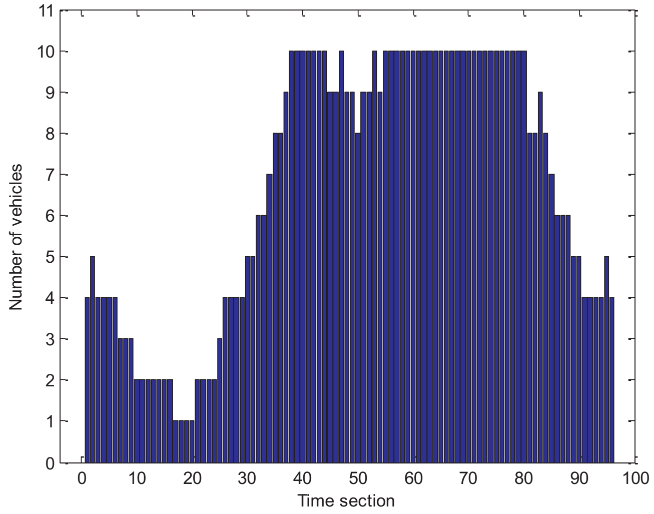

Fig. 3. The entered cars to the charging site during each period.

Table 1
Optimal design of multi-level charging facility.

	Fast charger	Intermediate charger	Slow charger
Rated power (kW)	116.0	84.00	52.00

Table 2
Optimal design of battery energy storage.

	Rated power (kW)	Rated capacity (kWh)
Optimal level	133.3	155.3

Table 3
Optimal design of line reinforcement.

Reinforced lines	Reinforcement level (%)
Lines between bus 1 to bus 10	183

Innovations of the model

The most important novelties of the developed model are summarized here;

Table 4
Annualized costs of charging station.

Item	Cost (10^3 $/year)
Energy of charging station	654.7
Battery energy storage	9.4
Charging facility	114.3
Constructing charging station	4.1
Network reinforcement	148.9
Wind turbine	13.2
Total	944.5

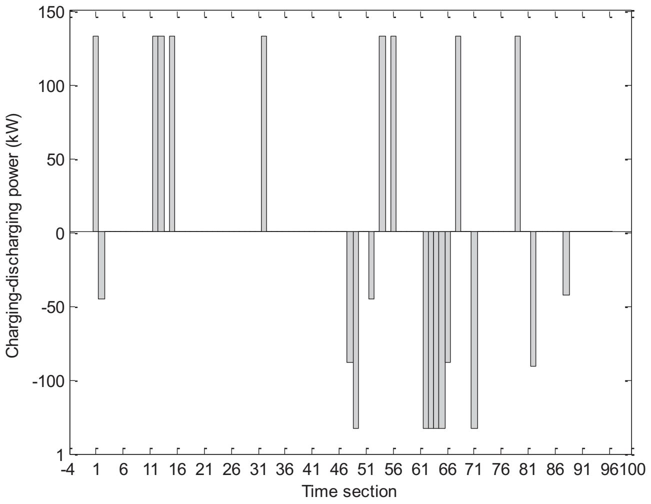

Fig. 4. Optimal operation pattern of battery storage system.

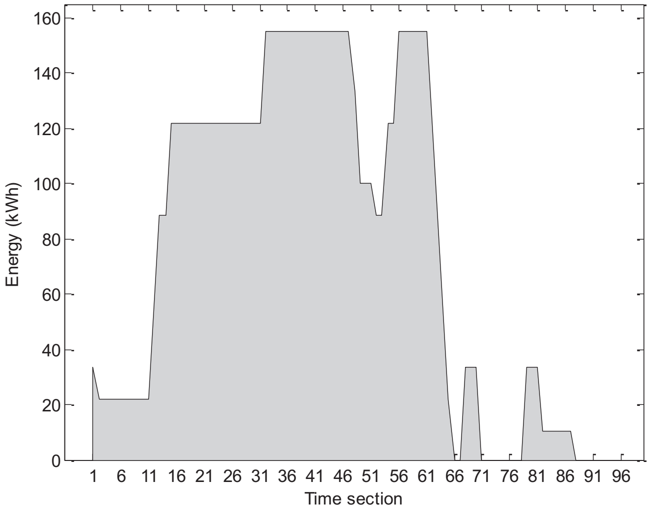

Fig. 5. The energy inside storage system.

- Modeling the combination of multi-level charging facility, wind energy, energy storage system, and network reinforcement simultaneously.
- Considering power, capacity, and operation pattern of all components as design variable.
- Optimization of all variables incorporating the uncertainties through stochastic programming.
- Evaluating the interaction among the energy resources, capacity resources, and components.
- Evaluating the interaction between the charging station and electrical grid.
- Studying the interaction between the electric vehicles operation and

Table 5
Impacts of battery storage system and network reinforcement on each other.

		Planning cost (10^3 \$/year)	Planning results
Case 1	Removing battery storage system	972.5	Network reinforcement = 185%
Case 2	Limited reinforcement to 150%	1020.4	Rated power of battery = 501 kW Rated capacity of battery: 2638 kWh

Table 6
Results of sensitivity and error analysis.

Item	Planning cost (10^3 \$/year)	Planning results
Increment of battery price by 50%	951.2	Parking capacity = 13 Rated power of battery: 0 Rated capacity of battery: 0 Reinforcement = 196%
Increment of charging facility price by 100%	1058.6	Parking capacity = 14 Fast speed charger = 108 (kW) Intermediate speed charger = 74 (kW) Slow speed charger = 36 (kW)
Increment of reinforcement price by 100%	1089.8	Parking capacity = 13 Rated power of battery: 184.7 kW Rated capacity of battery: 244.6 kW Reinforcement = 176%

Table 7
Outputs of the plan after increasing the capacity of electric vehicles by 50%.

Parameter	Value
Quick charger (kW)	256.0
Intermediate speed charger (kW)	180.0
Slow charger (kW)	96.00
Capacity of station (kW)	17.00
Power of battery (kW)	0.000
Capacity of battery (kW)	0.000
Reinforcement (%)	276
Planning cost (10^3 \$/year)	1997.554
Energy cost (10^3 \$/year)	1505.661

Table 8
The arriving cars to the station at first time period.

Vehicle Number	Initial Energy (kWh)	Charger Type	Charging Time-Interval	Charging Power (kW)	Final Energy (kWh)
1	07	Fast	5	96	60
			8	116	
2	25	Intermediate	5	84	60
			6	56	
3	49	Slow	5	44	60
4	53	Slow	1	28	60

peak load cutting.

- Minimizing various costs at the same time including cost of charging station capacity, storage system cost, charging facilities cost, and network reinforcement cost.
- Minimizing the energy of charging station.

Methodology and model

Fig. 1 shows the structure of the electric vehicle charging station. The station is supplied by energy storage unit, wind turbine, and multi-level charger including fast, intermediate, and slow speed charging facility. The station is linked to the electrical grid. The IEEE 33-bus radial distribution grid is adopted as case study [22]. The station is linked to the upstream grid at bus number 10.

The flowed power in the network lines are calculated by (1) and the capacity of lines is given by (2). The balance of power in all buses is explained by (3). The bus 10 which is equipped with charging statin is also modeled in (3) [22].

$$f^{l,m,n,o,p} = (\Theta^{l,m,o,p} - \Theta^{l,m,o,p}) \times a^{m,n}$$
$$\forall\, l \in L,\ \ m \in M,\ \ n \in N,\ \ o \in O,\ \ p \in P \tag{1}$$

$$\begin{cases} f^{l,m,n,o,p} \leqslant ff^{m,n} \\ f^{l,m,n,o,p} \geqslant -ff^{m,n} \end{cases}$$
$$\forall\, l \in L,\ \ m \in M,\ \ n \in N,\ \ o \in O,\ \ p \in P \tag{2}$$

$$ld^{l,m,o,p} + vd^{l,m,o,p} + \sum\nolimits_{n\in N}^{N} f^{l,m,n,o,p} = 0$$
$$\forall\, l \in L,\ \ m \in M,\ \ n \in N,\ \ o \in O,\ \ p \in P \tag{3}$$

The electric vehicle charging station is equipped with battery unit [23]. The operation of storage unit is modelled through (4) to (5). This model is taken from [22].

$$\begin{cases} cb^{m,o,p} \leqslant ccb^{m} \\ db^{m,o,p} \leqslant ccb^{m} \\ eb^{m,o,p} \leqslant eeb^{m} \end{cases}$$
$$\forall\, m \in M,\ \ o \in O,\ \ p \in P \tag{4}$$

$$eb^{m,o,p} = eb^{m,o,p-1} + (cb^{m,o,p} - db^{m,o,p})$$
$$\forall\, m \in M, o \in O, p \in P \tag{5}$$

The charging station is benefited from three-level charging system. The operation of three-level charging system is modelled through (6) to (8). The three-level charging facility includes slow, intermediate, and quick chargers [24]. The entered car uses the slow charger when the energy inside the battery is more than 66%. It is charged by intermediate charger if the energy of battery is between 33% and 66%, and otherwise it is charged by quick charger [22].

$$\begin{cases} ev^{l,m,o,p,q} = ev^{l,m,o,p-1,q} + \sum\nolimits_{z\in Z} (cv_z^{l,m,o,p,q} \times u_z^{l,m,o,p,q}) \\ \qquad \sum\nolimits_{z\in Z} (u_z^{l,m,o,p,q}) = 1 \end{cases}$$
$$\forall\, l \in L,\ \ m \in M,\ \ q \in Q,\ \ o \in O,\ \ p \in P,\ \ z \in Z \tag{6}$$

$$\begin{cases} ev^{l,m,o,p,q} \leqslant eev^{q} \\ cv_z^{l,m,o,p,q} \leqslant ccv_z \end{cases}$$
$$\forall\, l \in L,\ \ m \in M,\ \ q \in Q,\ \ o \in O,\ \ p \in P,\ \ z \in Z \tag{7}$$

$$N_{ev}^{l,m,o,p} \leqslant C_{evcs}$$
$$\forall\, l \in L,\ \ m \in M,\ \ o \in O,\ \ p \in P \tag{8}$$

The distribution network lines may need reinforcement to increase the capacity of lines in order to supply the charging station demand. The network reinforcement is modeled by (9) [22].

$$\begin{cases} f^{l,m,n,o,p} \leqslant ff^{m,n} \times R_r^{m,n} \\ f^{l,m,n,o,p} \geqslant -ff^{m,n} \times R_r^{m,n} \end{cases}$$
$$\forall\, l \in L,\ \ m \in M,\ \ n \in N,\ \ o \in O,\ \ p \in P \tag{9}$$

Eventually, the planning cost is calculated by (10). The first term represents the annualized cost of energy consumed by charging station. The second term shows the investment cost of energy storage system. The third term models the investment cost of charging system. The cost for constructing the station is given in the fourth term. The 5th term indicates the investment cost of network reinforcement and the 6th term introduces wind turbine investment cost. All the investment costs are annualized to achieve the annualized planning cost [22].

$$AC_{evcs} = \Big\{\sum_{o\in O}\sum_{l\in L}\sum_{p\in P}\sum_{q\in Q}\sum_{z\in Z}(cv_z^{l,m,o,p,q} \times u_z^{l,m,o,p,q} \times e_p^{o,p} \times pr^l \times t^o)\Big\} + \begin{pmatrix} \{eeb^m \times v_{erb} + ccb^m \times v_{prb}\} + \{\{\sum_{z\in Z} ccv_z\} \times C_{evcs} \times v_{cf}\} + \\ \{CC_{evcs}\} + \{R_r^{m,n} \times v^{m,n}\} + \{P_{wt} \times v_{wt}\} \end{pmatrix} \times Kcc \tag{10}$$

Correlation of strategies

There is a correlation between several parameters in the problem should be described. Increasing parking slots needs more investment cost but adding comfort for the drives. On the other hand, installing high power charging facilities results in less parking slots (i.e., less investment cost) because the vehicles can get fully charged faster and leave the station and free the space for new ones. However, high power charging facilities needs more investment cost. As a result, the planning deals with parking capacity, rated power of charging facilities, and wellbeing of drives at the same time and it finds the best solution for these parameters.

The other correlation is between peak shaving strategy and flexible charging time. In this paper a flexible charging time is assumed for the electric vehicles and the charging facility can interrupt the charging process in a time section and then continue to charging in the next time sections. However, total charging time must not exceed the defined and desired time by the operator. According to the such strategy, the charging station can defer charging time for on-peak time sections to the off-peak time periods and provide proper peak cutting in the grid.

As well, the battery energy storage system in the charging station are planned in coordination with charging facilities. As a result, this device can be properly planned to relive line congestion during peak time periods. In this paper, the time-of-use (TOU) energy pricing strategy is adopted. Therefore, the battery storage system supplies energy to the network during on-peak time-intervals resulting in proper peak-cutting.

Stochastic programming to deal with uncertainties

The produced power by wind generating system is modeled by probability distribution function (PDF). The initial energy inside the electric vehicle is also modeled by PDF. These two sources of uncertainty are dealt by scenario-generation and scenario-reduction method. First, many scenarios of performance are generated by sampling from the probability distribution functions. The backward scenario reduction technique is therefore operated to reduce the number of scenarios to the anticipated level. The details for scenario generation and backward scenario reduction techniques can be found in [25]. After achieving enough number of scenarios, the problem is solved under set of scenarios. The set of scenarios in the planning is denoted by '*L*' and each scenario is addressed by '*l*'. The formulations show that all the equations of the problem are expressed including set of scenarios [26].

The network under study

The test network is shown in Fig. 1. The charging station is connected to bus number 10 in IEEE 33 bus distribution grid. The network data is taken from [27]. The seasonal power of wind turbine is depicted in Fig. 2 and its rated power is 50 kW [28].

Each day is divided into 96 time-intervals (each 15-minutes). In each time period, the variations of load, electric vehicles, and prices are neglected. In other words, each time interval can be considered as a deterministic scenario where number of vehicles, their charging power, prices, and the other parameters are constant [24]. The number of arrived cars to the station during each period are represented by Fig. 3 [29].

The initial energy of vehicles is modeled by Gaussian distribution with Mean 30, Standard Deviation 15%, and Positive Skewness 15%. The Positive Skewness shows that the initial energy of the arriving vehicles is possibly less than 50% of full capacity. The seasonal loading profile and the electricity price are taken from [22].

The capacity of electric vehicles is 60 kW and they need 2 h for full charging. The discount rate is assumed 10%. The life time of all assets is 10 years except the charging station building that has 15-year life time. Each vehicle needs 12 square meter space in the charging station. The length of each line in the distribution network is 2 km and it costs 50,000 $. The capital costs on power and capacity of storage system are 200 $/kW and 200 $/kWh, respectively. The capital cost on wind power and charging facility are 2000 $/kW and 200 $/kW, respectively. The capital cost for constructing station is 200 $ per square meter [22].

Results and discussions

The charging station is optimally designed by the proposed method. Table 1 shows the optimal rated powers for multi-level charging facility. It is clear that the fast, intermediate, and slow speed chargers are planned to minimalize the capital cost. Table 2 lists the optimal design of battery energy storage including optimal power and capacity. Table 3 also demonstrates the optimal design of line reinforcement; where, the lines before the charging station (before bus 10) are reinforced by 183% of their capacity. The optimal capacity of charging station is also achieved by 13 vehicles.

The annualized costs of infrastructures are listed in Table 4. The total planning cost is 944.5 $/year. The largest part of the cost is covered by consumed energy. The network reinforcement also plays a major role to increase the cost. The minimum cost is related to charging station building.

Management of storage system

The optimal operation pattern of battery storage system is optimized as Fig. 4. The storage system shifts electricity from off-peak hours to on-peak time-periods in order to decrease the lines congestion and cost. Fig. 5 shows the stored energy inside the storage system and the maximum capacity of storage system is 155.3 kWh.

Analyzing the impacts of battery and reinforcement

Two important options of the planning are the battery and line reinforcement. The impacts of these two items on each other are studied here. Table 5 indicates that removing battery energy storage system increases the reinforcement to 185%. The reason is the demanded power must be supplied by the network and it needs more reinforcement and line capacity when the batteries are not installed. On the other hand, limiting reinforcement to 150% significantly increases power and capacity of battery storage system to 501 kW and 2683 kWh, respectively. As a result, coordinated battery-reinforcement planning presented by this paper is the best option for the charging station.

Sensitivity and error analysis

The results of sensitivity and error analysis are listed in Table 6. The outputs indicate the precise trend of the simulations. As shown, when the battery energy storage price is increased, the planning does not install battery storage unit because of its high cost. On the other hand, the plan increases the reinforcement level to compensate lack of storage system. In the next case, increment of charging facility price results in smaller chargers while the capacity of station is increased. In other words, the station charges the vehicles with smaller chargers and the vehicles must spend more time in the station and more capacity is required as a result. Increment of reinforcement price also shows that more battery is installed and less reinforcement is chosen by the plan to minimize the costs.

Electric vehicle capacity variation

In this case, the capacity of electric vehicles is increased by 50% and the results are given in Table 7. It is clear that the larger charging station and chargers are requited. The plan uses more reinforcement in the lines instead of installing battery energy storage systems. The results show that the battery is not installed because the required power of system can be supplied by the new reinforced lines and it is not needed to install battery in the charging station.

Operation of charging facility

The multi-level charging facility optimally charges the electric vehicles to minimize the charging time. The operation of charging facility under first time interval is listed by Table 8. The vehicles are charged by fast, intermediate, and slow speed charging facilities depending on their initial energies. The first vehicle has 7 kWh initial energy and it is charged by fast speed charger. The second vehicle has 25 kWh initial energy and it is charged by intermediate speed charger. The two last vehicles are charged by slow speed charger because of their high initial energy. All vehicles are finally charged to 60 kWh.

Conclusions

The proposed model successfully designed the electric vehicle charging station. The optimal rated powers of multi-level charging facility are designed on 116.0, 84.00, and 52.00 kW for fast, intermediate, and slow speed chargers, respectively. The power of quick charging system is greater than the intermediate one by about 27% and the intermediate charging system also needs 38% more power compared to the slow charging system. The power and capacity of battery are adjusted on 133.3 kW and 155.3 kWh, respectively. Such large rated power means that the storage system can discharge 85 percent of its energy during one hour. The network reinforcement is set on 183% to cope with energy demand from the charging station. The total cost is 944.5 $/year and about 70% of the cost is related to the energy demanded by station. The network reinforcement makes about 15% of the cost and the charging facility forms about 12% of total cost. The other items like storage system, station building, and wind turbine do not show significant costs. The storage system shifts energy from the time periods like 61–66 to the time intervals like 12–16 in order to reduce the lines congestion and cost. The results demonstrate that removing battery energy storage system increases the reinforcement to 185% and on the other hand, limiting the reinforcement to 150% significantly increases the power and volume of battery to 501 kW and 2683 kWh, respectively. It is also verified that the fast charger is applied to supply the electric cars with the initial energy less than 20 kWh, the cars with the energy between 20 and 40 kWh are supplied by intermediate charging system, and the other cars are supplied by slow system.

Further to this work, it may be useful to model the solar energy rather than the wind energy in the model. The solar system shows more uncertainty and fluctuations than the wind energy. As a result, the system integrated with solar energy comprises more fluctuations and the control on the storage could be different.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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