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Citation: Bagheri Tookanlou, Mahsa, Marzband, Mousa, Kyyra, J., Al Sumaiti, A. and Al. Hosani, K. (2020) Charging/Discharging strategy for electric vehicles based on bi-level programming problem: San Francisco case study. In: 2020 IEEE 14th International Conference on Compatibility, Power Electronics and Power Engineering (CPE-POWERENG): 8-10 July 2020, Online - Setúbal, Portugal. Proceedings . IEEE, Piscataway, NJ, pp. 24-29. ISBN 9781728142197, 9781728142180

Published by: IEEE

URL: https://doi.org/10.1109/cpe-powereng48600.2020.916... <https://doi.org/10.1109/cpe-powereng48600.2020.9161485>

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Charging/Discharging strategy for electric vehicles based on bi-level programming problem: San Francisco case study

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***Abstract*—The increasing market share of electric vehicles (EV)s leads to determine a proper strategy for charging/discharging EV batteries such that rewards of all agents including EV charging stations (EVCS)s and EV owners (EVO)s that participate in charging/discharging EV batteries are guaranteed. In this study, an economical and technical strategy is developed. It focuses on finding proper EVCSs by EVOs and determining optimal hourly electricity prices traded between all agents such that the rewards of EVCSs and EVOs are met simultaneously. This optimal charging/discharging decision making and optimal hourly electricity prices are determined by bi-level programming problem (BLPP). The outer level corresponds to the optimization problem of EVCSs and the inner level belongs to EVOs. Particle swarm optimization (PSO) algorithm is utilized to solve BLPP. Based on determination of minimum distance travelled by EVOs and optimal hourly electricity prices offered by EVCSs, the rewards of EVCSs and EVOs are analysed during charging/discharging period. For simulation purposes, a case study based on San Francisco in US is presented to visualize and validate the modelling results. Six EVCSs are installed in San Francisco for charging/discharging EV batteries during 24 hours of a typical day. Simulation results show that under implementing the proposed charging/discharging strategy, the expenses of EVCSs and EVOs spent for charging/discharging EV batteries decline such that the total costs of EVCSs and EVOs decrease by 27.3% and 24.6%, respectively, in comparison with not considering the proposed strategy.**

***Index Terms*—Bi-level programming problem, charging/discharging decision, electric vehicles, electricity pricing.**

NOMENCLATURE

a	Rate of harmonic current in the input of the charging device of EVCS
A	Area of PV (m^2)
B	Reliability coefficient of the charging device of EVCS
c_{1f},c_{2f}	Final values of acceleration coefficients
c_{1i},c_{2i}	Initial values of acceleration coefficients
C	Cost ($)
Cp	Capacity (kWh)
C_1,C_2	Cognitive and social acceleration coefficients
d	Greenhouse gasses density of electricity power (kg/kWh)
E	Total greenhouse gas emissions (kg)
f	Efficiency
HV	Heat value (kWh/m^3)
$it/\overline{it}$	Number/Maximum number of iteration
In	Revenue ($)
Ir	Solar radiation (W/m^2)
I_0	Inertia weight
I_1/I_2	Initial/final value of inertia weight
k	Overall correction coefficient of EVCS
L	Simultaneity coefficient of the charging devices
MCP	Market clearing price ($/kWh)
$\overline{N}$/N	Maximum number/Number
OF	Objective function
p	Electricity price ($/kWh)
P	Active power (kW)
PF	Power factor
$rand_1, rand_2$	Random numbers between 0 and 1
SOC	State of charge of battery (%)
$\overline{SOC}$/$\underline{SOC}$	Maximum/Minimum SOC
T	Temperature (°C)
Δt	Time step (s)
v	Velocity vector
w_1,w_2	Weighing factor
X	Position vector
Superscript	
am	Ambient
$A+, B$	A purchases electricity from B (A: EV, CS and B: EV, CS, EM)
$A-, B$	A sells electricity to B (A: EV, CS and B: EV, CS)
$A \rightarrow B$	Travel from A to B (A: EV^{OR}, CS^{SE} and B: CS^{SE}, EV^{DE})
CD	Charging device
CS	EVCS
DP	Departure

EM	Electricity market
ESS	ESS
EV	EV
EV^{DE}	Destination of EV
EV^{OR}	Origin of EV
g	Global
gas	Natural gas
k	Number of particles
MT	Microturbine
in	Initial
Oc	Occupied
Op	Operation
PQ	Active electricity power filtering and reactive electricity power compensation
PV	PV system
R	Required
M	Electricity market
y	Particle best position
$\pm$	Charging/Discharging

subscript

h	Hours of a day
i	Index of EVCSs
it	Iteration
j	Index of charging devices
k	Index of EV
$p.u$	Per-unit

I. INTRODUCTION

Electric vehicles (EV)s have experienced a favourable growth recently due to their economic and environmental benefits. While EVs enter the market on a large scale, choosing a proper EV charging stations (EVCS)s by EV owners (EVO)s in order to charge and discharge EV batteries and determining electricity prices traded between them have been regarded to be the most significant challenges.

In the literature, numerous studies have been investigated on optimal strategy for charging/discharging EVs. In [1], [2], an intelligent management and charging/discharging scheduling model were presented for EVs in a parking lot. The economic and technical features of charging/discharging EVs were considered simultaneously. In [3], an optimization model based on two objective functions was proposed under demand response program to consider both economic and environmental matters of a parking lot. Based on the presented model, consumers change the time of energy used and this has significant impacts on the performance of parking lot economically and environmentally. In [4], [5], optimal charging/discharging scheduling of EV aggregators is studied to minimize the carbon dioxide (CO2) emissions. In [6], a programming model was formulated to minimize the entire investment cost of EVCS and energy loss. In that study, optimal size, location, and planning of the fast EVCS are determined. In [7], charging schedules of electric freight vehicles were modelled and analysed that operated fixed delivery routes and performed several routes per day. A mathematical model that includes numerous attributes were presented. The features were related to the use of electric freight vehicles including a realistic process of charging, energy costs, battery aging, restrictions of electricity network, and facility related demand charges. In [8], EV charging scheduling was studied. The objective is to minimize the cost of EV battery aging such that the features of EV battery charging are satisfied. An algorithm is proposed for charging numerous plug-in hybrid EVs at a municipal EVCS. The objective function is maximization of SOC. The optimal charging electricity price, remaining battery capacity, remaining charging time and age of the battery are taken into account as constraints [9]. In [10], a smart scheduling approach was presented for planning EVCSs in a highway and minimizing the total time of travel for each EV. Waiting times and overall travel times decrease significantly using the proposed approach, consequently, it lead to the more profitable utilization of resources. In [11], a parking lot was studied in order to control EVs for minimization of operation expenses.

The review of available literature indicates that the following shortcomings (Sh) related to charging/discharging of EVs and EVCSs have been identified:

- Sh1: No solution is proposed to guarantee the rewards of EVCSs and EVOs participating in charging/discharging EV batteries, simultaneously.
- Sh2: There is no mathematical tool to study and model interactions between all EVCSs and EVOs.
- Sh3: EVOs do not select proper EVCSs for charging/discharging EV batteries in a competitive electricity market based on minimum driving distance and minimum expenses.
- Sh4: There is no competitive markets for the EVCS level for selling electricity to EVOs.
- Sh5: No electricity price calculation has been done based on guaranteeing the rewards of EVCSs and EVOs, simultaneously.

A. Contributions

The goal of this study is to propose an economical and technical charging/discharging strategy which mainly focuses on finding proper EVCSs by EVOs. Based on this strategy, EVOs select proper EVCS for charging/discharging their own EV batteries depending on the minimum driving distance and minimum expenses paid in the selected EVCSs. The minimum driving distance is determined by the Network Analyst toolbox of ArcGIS. The proposed strategy takes into account rewards of EVCSs and EVOs, simultaneously, based on bi-level programming problem (BLPP). Particle swarm optimization (PSO) algorithm is used to solve BLPP. Furthermore, optimal hourly electricity prices offered by EVCSs during charging/discharging period are determined. In general, the main contributions of this paper are:

- C1: Proposing BLPP to model the interaction between EVCSs and EVOs that participate in charging/discharging EV batteries to analyze the rewards of EVCSs and EVOs, simultaneously. (met sh1 and Sh2).

- C2: Presenting an optimal strategy to select proper EVCSs by EVOs in order to charge/discharge EV batteries (met Sh3).
- C3: Determining optimal hourly electricity prices traded between EVCSs and EVOs in a competitive electricity market (met Sh4 and Sh5).

This paper is structured as follows. Section 2 describes the system presented for charging/discharging EV batteries. The formulation of BLPP is presented in section 3. The PSO algorithm utilized for solving BLPP is explicated in Section 4 and, in section 5, the simulation results are presented. Finally, conclusions of the proposed strategy are given in Section 6.

II. SYSTEM DESCRIPTION

In this study, EVCSs with known locations are installed in a city and operate in parallel with the distribution network. Microturbine (MT), photovoltaic (PV) system, and energy storage system (ESS) are installed in each EVCS to supply electricity for each EV. If power produced by the MT and PV system and energy stored in ESS are less than the electricity required for charging EV batteries, the remaining required electricity is purchased from distribution network. All EVCSs have DC rapid charging devices. Thus, the charging/discharge time of each EV battery takes only one hour. The process for implementing the proposed strategy is shown in Fig. 1. Firstly EV parameters must be determined. There is a number of EVs with known origin, destination, and initial SOC. The minimum driving distance of each EV is obtained based on its origin and destination by Network Analyst toolbox of ArcGIS. After determining the required SOC of each EV, the charging/discharging mode of each EV is determined based on its initial SOC.

The relationship between EVCSs, and EVOs is modelled using BLPP. As shown Fig. 1, based on the charging/discharging mode of each EV, the proper EVCSs must be selected by solving BLPP. The optimization problem in outer level is related to the minimization of total cost of EVCSs and total greenhouse gas emissions. The hourly electricity price purchased by EVOs during charging period are determined in outer level. The inner level belongs to EVOs where the hourly selling electricity price to EVCSs during discharging period is determined by minimization of total cost of EVOs and required SOC of EV batteries. If EVCSs offer high prices, EVOs will not purchase electricity from EVCSs. Also, if EVCSs offer too low of prices, their total costs are not minimized. The EVOs receive hourly electricity price offered by each EVCS. During charging period, each EVO select a proper EVCS based on the minimum total required SOC and total expenses for charging their batteries. Also, during discharging period, a proper EVCS is selected based on minimum required SOC and maximum income of EVOs.

III. MATHEMATICAL MODELING

The optimization problems for both levels of BLPP and related objective functions and constraints of EVCSs and EVOs are formulated in this section.

A. *Objective function in outer level*

The total cost of EVCSs and total greenhouse gas emissions must be minimized in outer level, as given by

$$OF^{CS} = w_1^{CS} \times C^{CS} + w_2^{CS} \times E^{CS} \tag{1}$$

The total cost of EVCSs, as the first term in (1), is the difference between the costs of EVCSs and the income obtained by electricity sold to EVOs. The costs of EVCSs include the operation cost and the cost of electricity purchased from electricity market during charging period and from EVOs during discharging period, as obtained by

$$C^{CS} = C^{Op,CS} + C^{Pur,CS} - In^{CS} \tag{2}$$

The operation cost of each EVCS includes the operation costs of the MT and charging devices. The operation cost of MT is obtained by [12]

$$C^{Op,MT} = \sum_{h=1}^{24} \sum_{i=1}^{N^{CS}} \frac{P_{h,i}^{MT} \times p_h^{gas}}{f_{h,i}^{MT} \times HV} \tag{3}$$

The operation cost of charging devices corresponds to the cost of filtering for active power and the cost for compensation of reactive power, as given by [13]

$$C^{Op,CD} = \sum_{i=1}^{N^{CS}} c_{p.u,i}^{PQ} \times L_i \times k_i \sum_{j=1}^{N_i^{CD}} B_{i,j} \times a_{i,j} \times \frac{P_{i,j}^{CD}}{f_{i,j}^{CD} \times PF_{i,j}^{CD}} \tag{4}$$

The total costs of purchased electricity include the cost of electricity purchased from electricity market and from EVOs. The cost of electricity purchased from electricity market is determined by product of electricity purchased from electricity market and market clearing price (MCP), as given by

$$C^{CS+,EM} = \sum_{h=1}^{24} \sum_{i=1}^{N^{CS}} P_{h,i}^{CS+,EM} \times MCP_h^W \tag{5}$$

The cost of purchased electricity from EVOs is determined by product of power purchased from EVOs and the electricity price offered by EVCSs, as obtained by

$$C^{CS+,EV} = \sum_{h=1}^{24} \sum_{i=1}^{N^{CS}} \sum_{k=1}^{N^{EV}} P_{h,i,k}^{CS+,EV} \times p_h^{CS+,EV} \tag{6}$$

The income of selling electricity to EVOs is given by

$$In^{CS-,EV} = \sum_{h=1}^{24} \sum_{i=1}^{N^{CS}} \sum_{k=1}^{N^{EV}} P_{h,i,k}^{CS-,EV} \times p_{h,i}^{\text{CS-,EV}} \tag{7}$$

The total generated greenhouse gases of EVCSs is obtained by sum of the product of power produced by the MT and its related emission density and the product of power provided by the electricity market and its related emission density, as given by [3]

$$E^{CS} = \left(\sum_{h=1}^{24} \sum_{i=1}^{N^{CS}} P_{h,i}^{MT} \times d_{h,i}^{MT} + P_{h,i}^{CS+,EM} \times d_{h,i}^{CS,EM} \right) \times \Delta t \tag{8}$$

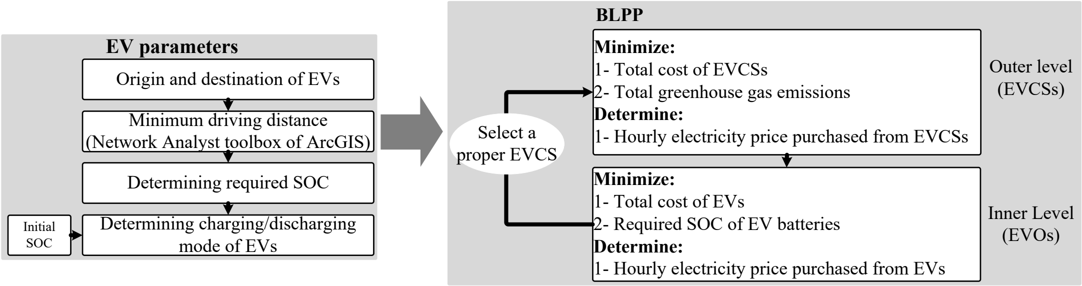

Fig. 1. Step-by-step process of implementing the proposed strategy for charging/discharging EV batteries.

The power produced by the PV system in each hour can be obtained by [3]

$$P_{h,i}^{PV} = f_i^{PV} \times A_i^{PV} \times Ir_h \times (1 - 0.005 \times (T_h^{am} - 25)) \tag{9}$$

The SOC of ESS in each EVCS can be determined by

$$SOC_{h,i}^{ESS} = SOC_{h-1,i}^{ESS} \pm \frac{P_{h,i}^{ESS\pm} \times \Delta t}{Cp_i^{ESS}} \tag{10}$$

B. Objective function in inner level

The total cost of EVOs and SOC required for EVs to reach their destination must be minimized in inner level, as given by

$$OF^{EV} = w_1^{EV} \times C^{EV} + w_2^{EV} \times SOC^{R,EV} \tag{11}$$

The total cost of EVOs is the difference between the cost of electricity purchased from EVCSs during charging period and the revenue from selling electricity to EVCSs during discharging period.

$$C^{EV} = C^{EV+,CS} - In^{EV-,CS} \tag{12}$$

The cost of electricity purchased from EVCSs is the product of power required for charging the EV batteries and the electricity price offered by EVCSs, as given by

$$C^{EV+,CS} = \sum_{h=1}^{24} \sum_{k=1}^{N^{EV}} P_{h,i,k}^{EV+,CS} \times p_h^{EV+,CS} \tag{13}$$

The revenue of EVOs from selling electricity to EVCSs is determined by

$$In^{EV-,CS} = \sum_{h=1}^{24} \sum_{i=1}^{N^{CS}} \sum_{k=1}^{N^{EV}} P_{h,i,k}^{EV-,CS} \times p_{h,i}^{EV-,CS} \tag{14}$$

The total required SOC of EV batteries, as the second item in (11), is obtained by (15). The total required SOC is the difference between sum of the SOC required to reach to the EVCSs from origin of EVs and the SOC required to reach the destination of EVs from location of the EVCSs and initial SOC.

$$\begin{aligned} SOC^{R,EV} = \sum_{h=1}^{24} \sum_{k=1}^{N^{EV}} \Big(& SOC_{h,k}^{R,EV^{OR} \to CS} \\ & + SOC_{h,k}^{R,CS \to EV^{DE}} - SOC_{h,k}^{in} \Big) \end{aligned} \tag{15}$$

The SOC of EV batteries in each hour can be determined by [1]

$$SOC_{h,k} = SOC_{h-1,k} \pm \frac{P_{h,k}^{EV\pm,CS} \times \Delta t}{Cp_k^{EV}} \tag{16}$$

The charging/discharging mode of EV batteries can be determined by comparison between initial SOC of each EV and the SOC required to reach the destination of EV from the EV's origin. If the initial SOC is less than required SOC to reach the EV's destination, the mode of EV is charging. Also, if the initial SOC is more than required SOC to reach the EV's destination, the mode of EV is discharging.

C. Constraints

The constraints of EVCSs and EVOs for objective functions in inner and outer level obtained by (1) and (11), respectively, are presented in this section.

1) Constraints in outer level: In each EVCS, balance between supply and demand must be achieved at each hour, as given by

$$\begin{aligned} & P_{h,i}^{PV} + P_{h,i}^{MT} \pm P_{h,i}^{ESS\pm} + P_{h,i}^{CS+,EM} + \sum_{k=1}^{N^{EV}} P_{h,i,k}^{CS+,EV} \\ & = \sum_{k=1}^{N^{EV}} P_{h,i,k}^{CS-,EV} \end{aligned} \tag{17}$$

The number of charging devices being available for charging EV batteries in each EVCS is limited for each hour.

$$N_{h,i}^{Oc,CD} \leq \overline{N}_i^{CD} \tag{18}$$

The SOC of the ESS for each EVCS is limited by

$$\underline{SOC}_i^{ESS} \leq SOC_{h,i}^{ESS} \leq \overline{SOC}_i^{ESS} \tag{19}$$

Charging and discharging ESS is not possible simultaneously.

$$P_{h,i}^{ESS+} \times P_{h,i}^{ESS-} = 0 \tag{20}$$

The electricity price offered by EVCSs to EVOs during charging period must be more than MCP of electricity market for each hour.

$$MCP_h^M \leq p_{h,i}^{CS-,EV} \leq 2.5 \times MCP_h^M \tag{21}$$

In each EVCS, the power produced by the MT must be limited by maximum and minimum value [12]

$$0.3 \times Cp_i^{MT} < P_{h,i}^{MT} \leq Cp_i^{MT} \tag{22}$$

2) Constraints in inner level: The EV batteries must be charged such that the SOC at the departure time from selected EVCS is more than the required SOC of EV batteries.

$$SOC^{DP}_{h,k} \geq SOC^{R}_{h,k} \tag{23}$$

For each EV, during charging/discharging period, the SOC of batteries must not exceed the minimum and maximum value.

The electricity price offered by EVCSs to EVOs during discharging period must not be more than MCP of electricity market in each hour.

$$0 \leq p^{\text{EV-,CS}}_{h} \leq MCP^{M}_{h} \tag{24}$$

IV. OPTIMIZATION

In this section, the PSO algorithm is defined for optimization of BLPP. PSO algorithm is based on the behavior of a group of birds searching for food. In a search space, a position of a bird corresponds to each solution of the problem and it is known as a particle. Each particle has the best value of the objective function of problem. In each iteration, two parameters of particles including positions and velocities are determined and renewed based on the best solutions for each particle and the best global solutions [14].

$$\begin{aligned} v^{k}_{it+1} = K[I_0 \times v^{k}_{it} + C_1 \times rand_1(y^{k}_{it} - X^{k}_{it}) \\ +C_2 \times rand_{21}(y^{g}_{it} - X^{k}_{it})] \end{aligned} \tag{25}$$

$$X^{k}_{it+1} = X^{k}_{it} + v^{k}_{it+1} \tag{26}$$

The equilibrium between the global and local search is regulated by I_0. In this study, firstly, the high value is considered for inertia weight and then, in each iteration inertia weight value is declined. For each iteration, the value of inertia weight is determined by [14].

$$I_0 = (I_1 - I_2) \times \frac{\overline{it} - it}{\overline{it}} + I_2 \tag{27}$$

I_1 and I_2 are 0.9 and 0.4, respectively. To improve convergence for the global solution of the search, C_1 and C_2 are considered such that they are changed by time. Parameters C_1 and C_2 are determined based on [14].

$$C_1 = (c_{1f} - c_{1i}) \times it/\overline{it} + c_{1i} \tag{28}$$

$$C_2 = (c_{2f} - c_{2i}) \times it/\overline{it} + c_{2i} \tag{29}$$

$$K = \frac{2}{|2 - \varphi - \sqrt{\varphi^2 - 4\varphi}|} \tag{30}$$

$$\phi = C_1 + C_2 \tag{31}$$

1) PSO algorithm for solving BLPP: Solving BLPP by PSO algorithm starts from inner level. In inner level, a solution is obtained and applied to determine a solution for outer level. In the outer level, the dimension of each particle is (2)(Number of EVCSs×24) considering two sets of variables including optimal electricity price sold to EVOs by EVCSs and power produced by MT of each EVCS for 24 hours of a day. In inner level, the dimension of the particle is Number of EVCSs×24 that corresponds to optimal electricity price sold by EVOs to EVCSs for 24 hours of a day.

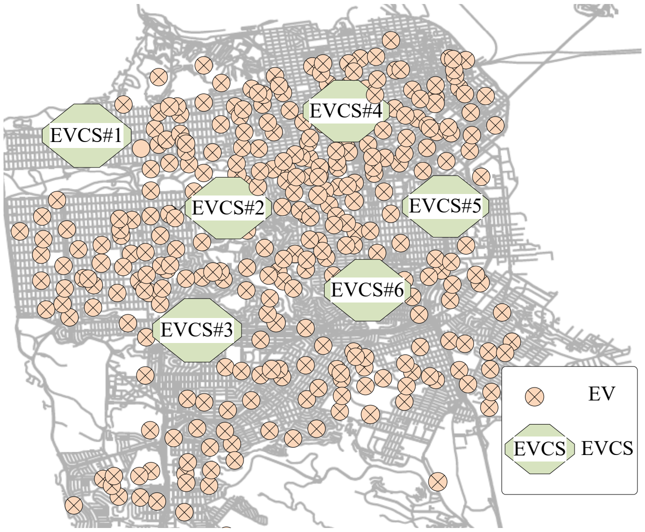

Fig. 2. Location of EVs and EVCS in San Francisco, US. during 24 hours of a typical day.

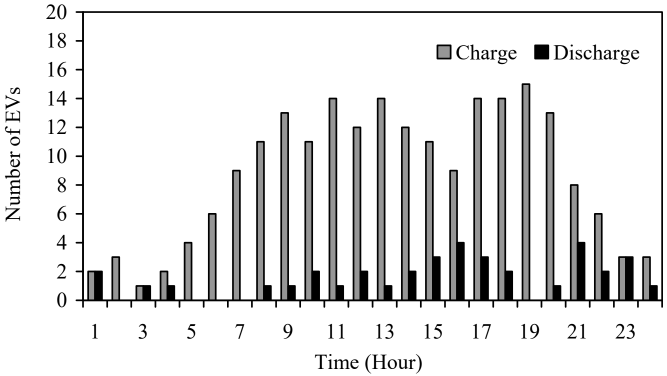

Fig. 3. Number of EVs in 24 hours of a day with different mode of battery.

V. SIMULATION RESULTS

For simulation purposes, as shown in Fig. 2, six EVCSs are installed in San Francisco which EVOs charge/discharge their own EV batteries there. As depicted in Fig. 3, during a day, 247 EVs with different mode of batteries are considered. The input parameters for EVCSs and EVs are presented in Table 1. MCP of electricity market for 24 hours of a typical day is shown in Fig. 4.

Based on optimal hourly electricity prices offered by EVCSs as depicted in Fig. 5 and Fig. 6 for charging and discharging mode of EVs, respectively, EVCSs are selected by EVOs.

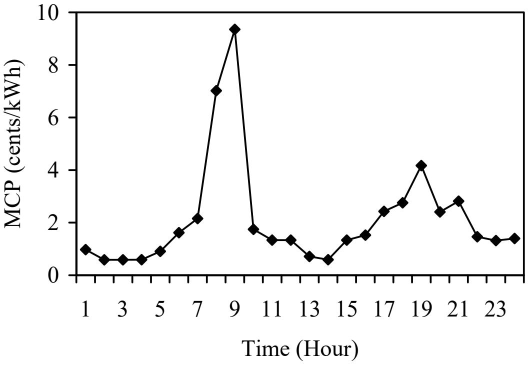

Fig. 4. MCP of electricity market in each hour of a typical day [15]

TABLE I
INPUT PARAMETERS OF EVCSS AND EVS [12]–[14], [16]

Parameter	Value	Parameter	Value
f^{CD}	0.9	f^{PV}	0.157
PF^{CD}	0.95	A^{PV}	800 (m^2)
Cp^{MT}	65 (kWh)	Cp^{ESS}	50 (kWh)
$\overline{N}_i^{CD}$	5	p^{gas}	0.3 (\$/m^3)
a	0.03	B	1.05
d^{MT}	0.36 (kg/kWh)	$d^{CS+,EM}$	0.56 (kg/kWh)
k	0.61	Cp^{EV}	28, 40 (kWh)
L_i	1	$c_{p.u,i}^{PQ}$	10.16 (\$/kVA)
$\underline{SOC}^{ESS}$/ $\overline{SOC}^{ESS}$	0.1/0.9	Δt	1 hr

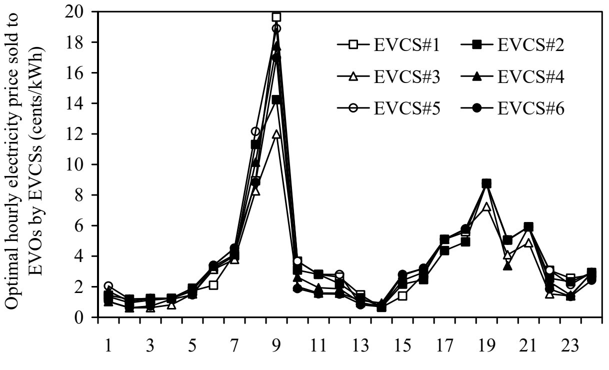

Fig. 5. Optimal hourly electricity price sold to EVOs by EVCSs during charging EV batteries.

During charging mode, EVCS#2 and EVCS#4 are selected by most of the EVOs such that 24.95% and 21.1% of EVOs select EVCS#2, and EVCS#4, respectively. However, only 12.85% of EVOs select EVCS5 and EVCS6. During discharging mode, EVCS#3 is selected by most of the EVOs such that 64.86% of EVOs select EVCS#3. Also, EVCS#1 is not selected by any EVOs. The comparisons between the total cost of each EVCS and EVOs for a typical day with considering and without considering the proposed charging/discharging strategy indicates that the employment of the strategy and obtained optimal hourly electricity prices has resulted in lower cost of EVCSs and EVOs. As a result, if the strategy for charging/discharging EV batteries is implemented, the total cost of EVCSs and EVOs decreases by 27.3% and 24.6%, respectively, in comparison without considering the proposed strategy and optimal hourly electricity prices.

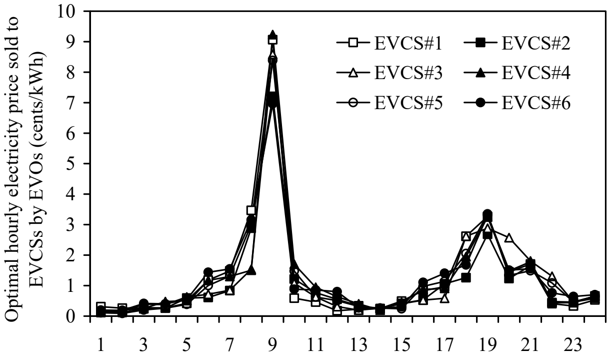

Fig. 6. Optimal hourly electricity price sold to EVCSs by EVOs during discharging EV batteries.

VI. CONCLUSION

In this study, an economical and technical strategy is presented to find proper EVCSs by EVOs in order to charging/discharging EV batteries. Based on determination of minimum driving distance specified by a navigation system, and optimal hourly electricity prices offered by EVCSs during charging/discharging period in each hour, the rewards for all agents are analysed by BLPP. It is found that under implementing the proposed charging/discharging strategy, the expenses of EVCSs and EVOs spent for charging/discharging EV batteries decline such that the total costs of EVCSs and EVOs decrease by 27.3% and 24.6%, respectively, in comparison with not considering the proposed strategy.

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