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Power Management of a Smart Vehicle-to-Grid (V2G) System Using Fuzzy Logic Approach

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Abstract— Smart charging/discharging of Plug-in Electric Vehicles (PEVs) is definitely able to bring a significant cost benefit for both EV station owners and EV owners as well. To this end, this paper develops a Mamdani-based fuzzy strategy with the inputs including the forecasted and real PV generation data, electricity price, and the instantaneous state-of-charging (SOC). Moreover, the output power of PEVs is considered as the output of the proposed strategy. In order to attain further smooth and accurate power sharing for PEVs, varied output rules are assigned commensurate with the rated power of each PEVs. In addition, another fuzzy strategy is developed using the instantaneous SOC error to establish a specified SOC for PEVs at the departure time. While two PV panel profiles are taken into account, Simulation in MATLAB/Simulink environment presents accurate and acceptable results from SOC of PEVs, PEVs output power, prices and grid power.

Keywords— Smart Charging, Plug-in Electric Vehicles (PEVs), Fuzzy Logic Control, State-of-Charging (SOC).

I. INTRODUCTION

The numbers of electric vehicles (EVs) have been estimated to globally surpass 35 million [1] and 100 million [2] by 2022 and 2028, respectively. It provides this opportunity for researchers and industrial companies to deeply deal with smart charging of EVs especially based on the cost-benefit criteria in both Vehicle-to-Grid (V2G) and Grid-to-Vehicle (G2V) applications [3-4]. Among different optimal strategies for Electric Vehicles (EVs) [5], researches worked on techniques such as Escort Evolutionary Game [6], Reinforcement Learning Technique [7], Mixed Strategy [8], Linear Quadratic Gaussian [9], and Linear Programming [10].

But, in order to adopt smart charging/discharging algorithms for much more effective control of EVs, two rule-based control strategies have been proposed including Deterministic Rule-Based Methods (DRMs) and Fuzzy-Rule-

Based Controllers (FRCs) [11]. In DRMs, the rules are ascertained prior to the actual operation of the system under control. In contrast, FRCs are featured by robustness against uncertainty and easy adjustment as well [12]. In addition, FRCs have fast performance with significant computational burden mitigation and the excellent secession capability of multiple controllers [13]. As a consequence, as one of the most effective strategies for smart charging of EVs, it is highly worthy to investigate various kinds of FRCs in the frame of different industrial applications.

FRCs-based smart charging strategies focused on various industrial challenges [14]-[15]. For instance, a fuzzy control technique was proposed by [16] to assign power coordination between EVs and power grid against Point of Common Coupling (PCC) voltage fluctuations. In this technique, the final charging/discharging rate and SOC of EVs battery were taken into account. Also, in [17], a fully decentralized controller was designed based on fuzzy logic technique with the input parameters driven from the power grid, EV charger and EV battery pack. This technique was aimed to reach a suitable EV charger for regulating the charging current against power grid instability. On the other hand, an adaptive fuzzy was established to accurately execute the EV prioritization process for simultaneously attaining the storage utilization maximization and the charging cost minimization [18]. In order to highly achieve precise charging/discharging points for connected EVs in presence of uncertainties coming from the electric grid and EVs, a fuzzy logic control was proposed in [19] to manage the efficient power available in the EVs of the parking lot. A fuzzy strategy was incorporated by grid constraints to specify the score of each PEV in the charging process aiming to maximize the owner's satisfaction based on the delivered energy [20]. The FRCs were also employed in energy management of hybrid electric autonomous vehicle [21], the intelligent control of a

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vehicle-to-grid system [22], and Big Data Analysis Technology of PEVs [23].

In this paper, a fuzzy-based smart charging technique is proposed for the smart grid shown in Fig. 1 to attain an accurate charging and discharging states for PEVs. Since V2G discharging challenges [24] and minimum peak load [25] are two very important targets, in the proposed technique, the PEVs are intended for attaining the cost benefit when both V2G and load consumption are instantaneously taken into account. Hereby, it is aimed to increase the power injection from PEVs to power grid while the price is increasing as well. As another target, each PEV should have a specified SOC at the departure time. Consequently, a new fuzzy strategy is developed through the instantaneous SOC error with the specified SOC as the reference set-point. This paper organizes as the follows. Section I focuses on the literature review. Proposed Fuzzy-based smart charging strategy is developed in Section II. This section consists of two sub-sections including the charging/discharging control of PEVs and SOC setting at the departure time. These sub-sections also investigate the effects of PV power, price and SOC error on the PEVs output power. The simulation results including SOC of PEVs, PEVs output power, prices and grid power are discussed in Section III. Conclusion is presented in Section IV.

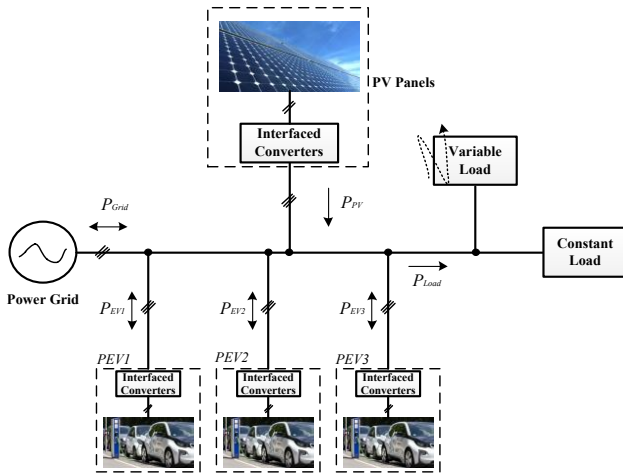


Fig. 1. The smart grid under study.

II. PROPOSED FUZZY-BASED SMART CHARGING STRATEGY

In this paper, the smart grid shown in Fig. 1 is taken into account. Based on this figure, the smart grid consists of three PEV, power grid, PV panels and load including both constant and variable loads. The power grid and PEVs are able to provide bidirectional power flow. The PV panels inject an unidirectional power to PCC with the profiles shown in Fig. 2(a). The total load has a profile according to Fig. 2(b).

A. The Charging/Discharging Control of PEVs

In order to reach the cost benefits, the PEVs in the considered smart grid should be managed through paying attention to minimum and maximum prices. On the other hand, knowing the variation trend of the PV power can facilitate reaching more cost benefit and utilization of PV panel power. Also, when SOC is monitored, it helps highly PEVs make a decision to stay at charging or discharging state. Based on the

smart grid in Fig. 1, the proposed smart charging/discharging strategy is aimed to achieve the following targets,

- The PV panels power must be utilized for charging the PEVs as much as possible.
- The power injection amount from PEVs to grid must be increased while the price is increasing as well.
- The charging process of PEVs must be prioritized by PV panels. But, the power injection amount from grid to PEVs must be increased while the price is decreasing.

Using the aforementioned targets and noticing the price profile depicted in Fig. 2(c), the proposed fuzzy strategy is devised based on the Table I.

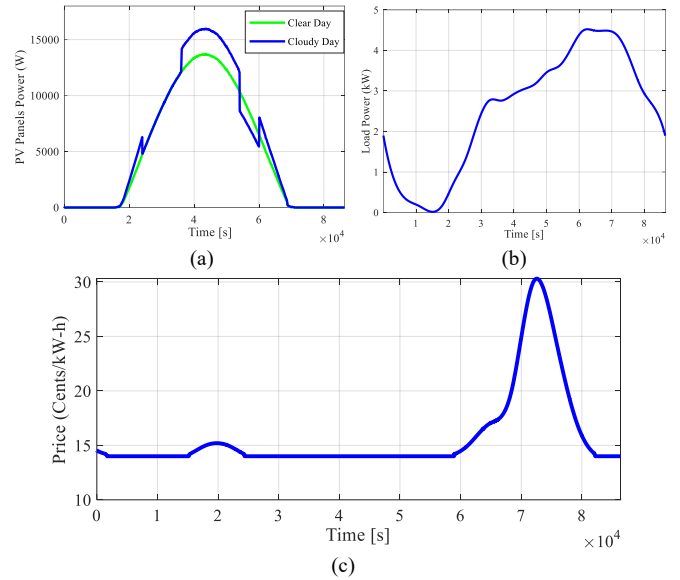


Fig. 2. (a) PV panel power profiles in two states of clear day and cloudy day, (b) Load power profile, and (c) the price profile.

As it can be seen from this table, the states of Low (L), Medium (M) and High (H) are defined for all SOC of PEVs, the PV panels power and the price. For the charging (C) and discharging (DC) modes in the output of fuzzy strategy, Very High (VH) and Zero (Z) are taken into consideration as well. The weight factor for each rule is set on "1" in this paper. The Mamdani Fuzzy Inference System (FIS) type with the Trapezoidal membership function are employed. A typical Trapezoidal membership function is illustrated in Fig. 3.

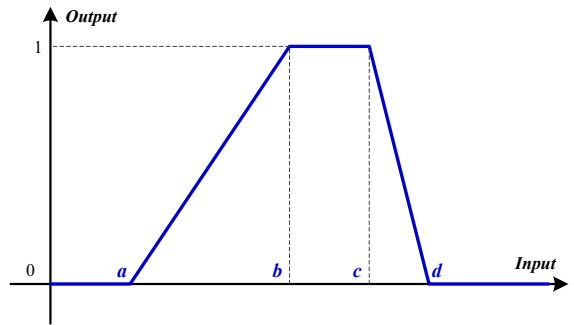


Fig. 3. Trapezoidal membership function for proposed Fuzzy strategy.

Table I. The rules of proposed fuzzy charging/discharging strategy for PEVs.

No	Inputs			Outputs			Weight of Rule	No	Inputs			Outputs			Weight of Rule
	SOC	Ppv	Price	PEV1	PEV2	PEV3			SOC	Ppv	Price	PEV1	PEV2	PEV3	
1	LS	Lpv	LP	MC	VHC	HC	1	15	MS	Mpv	HP	VHDC	VHDC	VHDC	1
2	LS	Lpv	MP	LC	MC	LC	1	16	MS	Hpv	LP	LC	HC	MC	1
3	LS	Lpv	HP	Z	Z	Z	1	17	MS	Hpv	MP	LC	MC	LC	1
4	LS	Mpv	LP	MC	VHC	HC	1	18	MS	Hpv	HP	VHDC	VHDC	VHDC	1
5	LS	Mpv	MP	MC	VHC	HC	1	19	HS	Lpv	LP	Z	Z	Z	1
6	LS	Mpv	HP	LC	MC	LC	1	20	HS	Lpv	MP	VHDC	VHDC	VHDC	1
7	LS	Hpv	LP	MC	VHC	HC	1	21	HS	Lpv	HP	VHDC	VHDC	VHDC	1
8	LS	Hpv	MP	MC	VHC	HC	1	22	HS	Mpv	LP	LC	MC	LC	1
9	LS	Hpv	HP	LC	HC	MC	1	23	HS	Mpv	MP	LC	MC	LC	1
10	MS	Lpv	LP	MC	VHC	HC	1	24	HS	Mpv	HP	VHDC	VHDC	VHDC	1
11	MS	Lpv	MP	VHDC	VHDC	VHDC	1	25	HS	Hpv	LP	LC	MC	LC	1
12	MS	Lpv	HP	VHDC	VHDC	VHDC	1	26	HS	Hpv	MP	LC	HC	MC	1
13	MS	Mpv	LP	LC	MC	LC	1	27	HS	Hpv	HP	VHDC	VHDC	VHDC	1
14	MS	Mpv	MP	LC	MC	LC	1								

Based on Fig. 3, the output of proposed Fuzzy strategy is obtained through (1),

$$f(x; a, b, c, d) = \begin{cases} 0, & x \leq a \\ \frac{x-a}{b-a}, & a \leq x \leq b \\ 1, & b \leq x \leq c \\ \frac{d-x}{d-c}, & c \leq x \leq d \\ 0, & x \geq d \end{cases} \quad (1)$$

Where x and $f(.)$ are the input and output of the fuzzy system, respectively. The parameters a , b , c and d are chosen by the designer and they can highly impact on the final value of the fuzzy system output. The relation (1) can be also stated as the following by using the S-norm function,

$$f(x; a, b, c, d) = \max \left(\min \left(\frac{x-a}{b-a}, 1, \frac{d-x}{d-c} \right), 0 \right) \quad (2)$$

According to Table III, the PEVs with different rated output power are exerted. It can be concluded that the charging and discharging rate differs for each PEVs. This point is employed to determine the Fuzzy rules for PEVs output power based on Table I. As it can be realized from this table, the charging and discharging rate is boosted in order as PEV1, PEV3, and PEV2. Also, in the proposed Fuzzy-based smart charging, the utilization of PV panel power takes priority over cost benefit when the SOC is in low level. This priority is seen in the rules 5, 6, 8 and 9, as given in Table I. In addition, excepted for the rules 6 and 9, all PEVs start discharging with very high rate when the price is high as determined in the rules 12, 15, 18, 21, 24, and 27. Using the Table I, a fuzzy rule-based 3D curve is achieved for each PEV based on the price and the PV panel power as it is depicted in Fig. 4.

In this figure, it can be understood when the price is increasing, all PEVs tend to be discharged more. It should be also noticed that the maximum discharging happens for PEVs when the PV panel power is approximately zero and the price is equal to its maximum value. On the other hand, as it can be figured out from Fig. 4(a), (b) and (c), in the midpoints of the

price and PV panels power, all PEVs reach the maximum charging from the proposed strategy point of view. In order to compare the Fuzzy rules performance for three PEVs, the PEV output power is plotted based on PV panel power and price in Fig. 5(a) and (b), respectively.

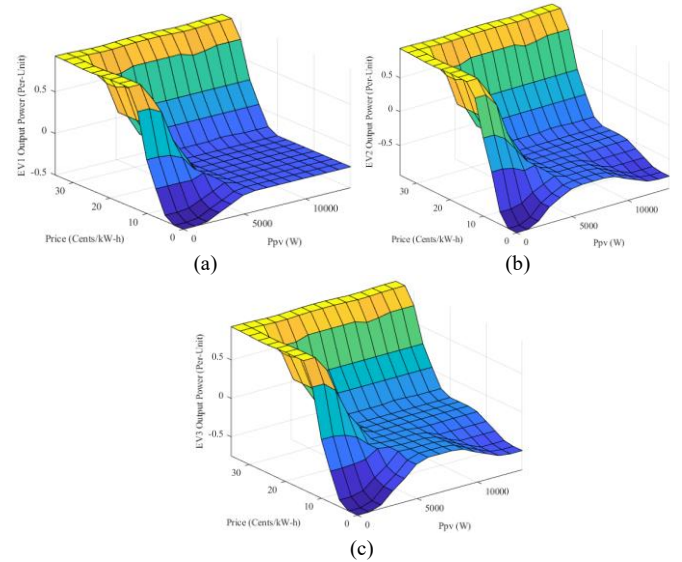


Fig. 4. The fuzzy rule-based 3D curves based on the price and the PV panel power for (a) PEV1, (b) PEV2, and (c) PEV3.

In both figures, it is obvious that the same results are achieved for the PEV1 and PEV2. Fig. 5(a) illustrates that there is the same trend for the output power of PEVs in which all PEVs are able to attain the maximum charging point after around $P_{pv}=6kW$. According to this figure, the PEV1 and PEV3 keep their discharging state in the interval $[0kW \ 4kW]$ which is more than the PEV2 within interval $[0kW \ 3.7kW]$. Within the mentioned intervals, the discharging rate of PEVs is continuously mitigated with a constant ramp as depicted in Fig. 5(a). It can be observed from Fig. 5(b) when the price is within the interval $[0 \text{ Cents/kW-h} \ 20 \text{ Cents/kW-h}]$, the output power of all PEVs is maximally charged. However, the PEV1 and PEV3 have less charging degree (-0.23 Per-Unit) in comparison with the PEV2 (-0.5 Per-Unit). It means that the PEV1 and

PEV3 save more money while the power grid is the responsible of charging the PEVs and the price is medium. Inversely, when the price is low and the power grid is the responsible of charging PEVs, the PEV2 can bring more cost benefit for both PEVs station owner and PEVs owner. But, after the price 20 Cents/kW-h, the discharging degree of all PEVs is increased with constant rate as depicted in Fig. 5(b). There is slight difference between the discharging trend of all PEVs, although the PEV1 and PEV3 have higher the discharging degree compared to the PEV2. It is worth mentioning when the price is going ahead its maximum value, all PEVs completely provide maximum power injection to the power grid as achieved in Fig. 5(b).

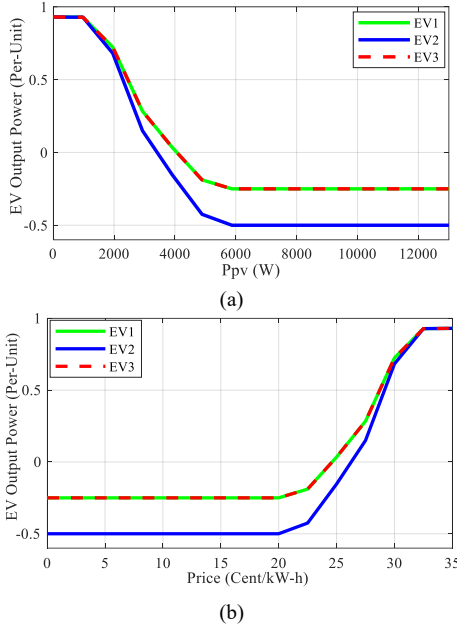


Fig. 5. Comparison between the Fuzzy rules of three PEVs output power based on (a) PV panel power, and (b) Price.

B. SOC Setting at the Departure Time

Another important target of the proposed smart charging/discharging strategy is to enforce the PEVs to have a specified SOC at the departure time from charging station. For SOC setting at the departure time, a new set of rules based on the instantaneous error of SOC is schemed as presented in Table II. The instantaneous SOC error is defined as the following,

$$e_{SOC}^i = SOC_{Final}^i - SOC^i \quad (3)$$

The proposed strategy in this sub-section utilizes the Mamdani FIS type with the Trapezoidal membership function as well. Thus, the output of the fuzzy strategy is achieved through,

$$PEV^i(e_{SOC}^i, a^i, b^i, c^i, d^i) = \max \left(\min \left(\frac{e_{SOC}^i - a^i}{b^i - a^i}, 1, \frac{d^i - e_{SOC}^i}{d^i - c^i} \right), 0 \right) \quad (4)$$

Where “ i ” stands for the i^{th} PEV ($i=1,2,3$). In Table II, the abbreviations of the symbols mean B (Big), M (Medium), L (Low), P (Positive) and N (Negative). As it can be seen from

Table II, the same rules are developed for PEV2 and PEV3, and different rules with less charging and discharging rate are made for PEV1 because of its higher-rated power. In order to compare the effects of the fuzzy rules on the charging/discharging degrees of the PEVs output power, Fig. 6 is plotted by using the rules in Table II. In Fig. 6, the inequalities of $e_{SOC}^i > 0$ and $e_{SOC}^i < 0$ mean that the PEV must be within the charging and discharging modes, respectively. To assess Fig. 6, as it is predicted, when the positive values of e_{SOC}^i is increased, the PEVs charging degree of proposed strategy must be increased as well. Moreover, inversely, while the negative values of e_{SOC}^i is decreasing, the PEVs output power should start discharging with constant rate.

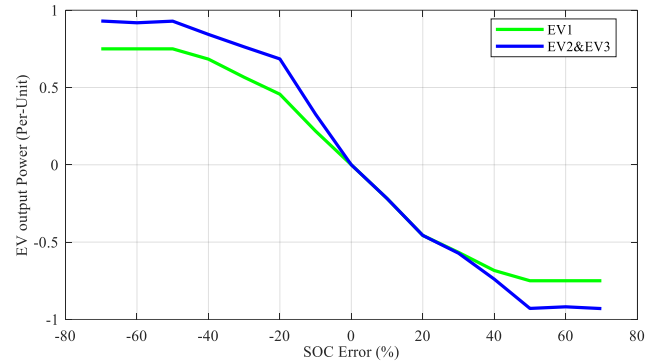


Fig. 6. Comparison between the charging/discharging degrees of the PEVs output power.

Table II. The rules for SOC setting at the departure time

no	1	2	3	4	5	6	7
e_{SOC}^i	BP	MP	LP	Z	LN	MN	BN
PEV1	HC	HC	MC	Z	MDC	HDC	HDC
PEV2	VHC	VHC	MC	Z	HDC	VHDC	VHDC
PEV3	VHC	VHC	MC	Z	HDC	VHDC	VHDC

TABLE III: THE PARAMETERS FOR SIMULATION TEST

Definition	Value
Rated maximum/minimum power of PEV1	22/-22 kW
Rated maximum/minimum power of PEV2	7.4/-7.4 kW
Rated maximum/minimum power of PEV3	11/-11 kW
Maximum/minimum PEVs SOC	90 %, 20 %
Final SOC for PEV1, PEV2 and PEV2	70%, 80%, 60%

III. SIMULATION RESULTS

The proposed smart charging/discharging strategy is evaluated through MATLAB/Simulink environment while two PV panels profiles are taken into account according to Fig. 2(a). The simulation parameters are demonstrated in Table III. As it can be seen from this table, the final SOC of three PEVs at departure time should be 70 %, 80 % and 60 %, respectively. The end of the simulation is considered as the departure time for all PEVs. According to Table III, the PEV2 has less rated power leading to bigger charging degree in the proposed Fuzzy rules compared to other PEVs as exhibited in Fig. 5. In addition,

the SOC in the rules of proposed fuzzy charging/discharging strategy is chosen between 20% and 90%. This section includes two sub-sections focusing on power analysis as well as the SOC and price analysis.

A. The Power Analysis

Fig. 7 shows the output power of three PEVs for clear and cloudy days. According to Fig. 7, using the proposed strategy, the PEV2 is set to be charged through PV panels much more than the PEV1 and PEV3 in both clear and cloudy days. After the PEV2 is fully charged, the PEV1 and PEV3 still remain at charging mode as depicted in Fig. 7(a) and (b). By noticing Fig. 2(c), the proposed smart charging/discharging strategy can be evaluated at the peak price. When the price is within its peak period, the proposed strategy is able to enforce the discharging mode with very high rate for all PEVs as can be observed from Fig. 7(a) and (b). Based on these figures, the PEV2, PEV3, and PEV1 contribute respectively to transforming power from PEVs to the grid.

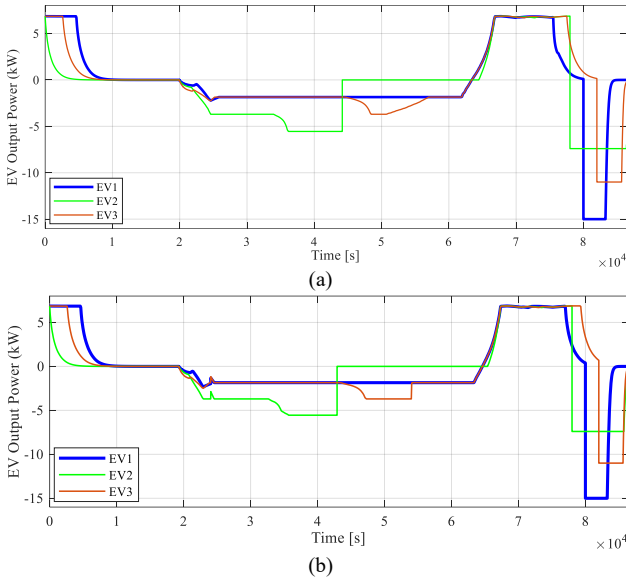


Fig. 7. The output power of three PEVs for (a) clear day, and (b) cloudy day.

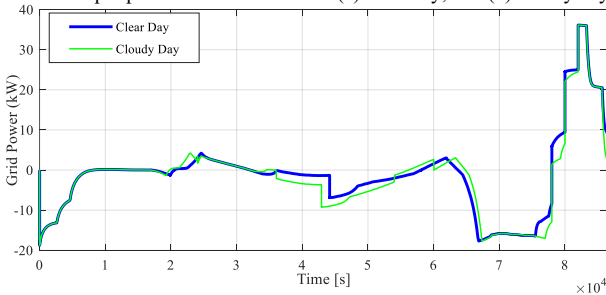


Fig. 8. The grid power for clear and cloudy days.

At the end of the simulation as the departure time of PEVs, all PEVs start charging to reach the finalized SOC_s stated in Table III. Fig. 8 illustrates the grid power for both clear and cloudy days. As it can be understood from this figure, when the PV panel power exists, the grid power is attempted to have less power generation and consumption. However, a peak power consumption happens for the grid immediately after full charging state of PEV2, as depicted in Fig. 8. On the other hand, it should

be pointed out that the grid power approaches its maximum power consumption when the price is located within its peak period shown in Fig. 2(c).

B. The SOC and Price Analysis

The proposed smart charging/discharging strategy can provide the SOC_s for three PEVs according to Fig. 9 when both clear and cloudy days are applied. As it can be seen from this figure, all SOC_s are continuously increased with the constant ramp within the interval which PV panels power reaches its peak values. Among the PEVs, the PEV2 has more charging rate as it has been assessed through Fig. 5. In comparison with the cloudy day, the PEV3 has been charged more in the cloudy day. In addition, all PEVs in the cloudy day have been more discharged while the price is within its peak values compared to the clear day. By noticing both Fig. 9(a) and (b), it can be realized that the proposed smart strategy is able to enable all PEVs to reach their finalized SOC at the departure time.

According to these figures, it is obvious that the PEV1, PEV2 and PEV3 can reach the SOC_s of 70 %, 80 % and 60 %, respectively with high accuracy and suitable transient time. As another target of this paper, the results of the price for both clear and cloudy days are illustrated in Fig. 10. This figure displays that high cost benefits can be obtained for both PEVs station and PEVs owners in all day. As it has been scheduled in the proposed smart charging/discharging strategy, when the price is within its peak values, the most cost benefits are driven as depicted in Fig. 10.

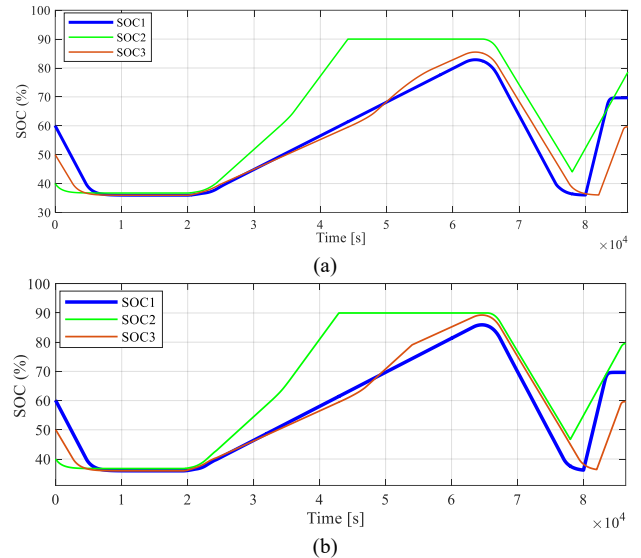


Fig. 9. The SOC of three PEVs for (a) clear day, and (b) cloudy day.

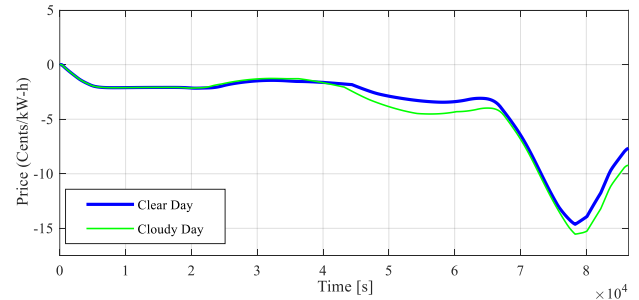


Fig. 10. The price for clear and cloudy days.

IV. CONCLUSION

A fuzzy-based smart charging/discharging strategy has been proposed in this paper to manage the output power of PEVs in a smart grid structure. The proposed strategy has consisted of two parts. The first part has been developed using a set of Mamdani FIS rules proportional to the rated output power of PEVs. This part has aimed to reach the utilization of PV panel power as well as bring cost benefits for the PEVs station owner and the PEVs owner. Several 3D and 2D curves have been obtained accordingly to assess the effects of the proposed fuzzy smart strategy on each PEV output power. As another main target of this paper, the second part has been allocated for the setting process of all PEVs SOC at a specified point when the PEVs have departed from the charging station. To this end, the instantaneous SOC errors have been incorporated by the proposed fuzzy rules for PEVs with varying charging/discharging degrees. Simulation results in MATLAB/Simulink environment have been achieved to verify the validity of the proposed strategy in presence of different PV panel profiles.

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