Energy trading framework for electric vehicles: an assignment matching-theoretic game

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Abstract: Electric Vehicles (EVs) can be considered as a flexible source of energy which can receive some benefit in terms of incentives for selling their energy. For efficient and economic trading amongst the EV owners, various researchers have proposed a variety of preference based matching algorithms like College Admission Framework (CAF), Max-weight, Merge and Split, Gale-Shapley Algorithm and Brute-Force Algorithm etc, where buyer and seller EVs can exchange energy and receive better payoffs. Unlike the above mentioned algorithms, in this paper the participating entities do not submit the preferences menu (which contains preferred choices of sellers (of a buyer) and of buyers (for a seller)) to a central authority. However, this paper proposes an assignment energy trading game where no central authority is needed, the matching algorithm is hosted on cloud which matches charging and discharging of EVs based on their aspiration level and bids. The contribution of the work is to deduce the bids and aspiration level of charging and discharging EVs which is not considered in any of the existing work. Widespread adoption of electric vehicles (EVs) can have some adverse effects on the grid due to a subsequent increase in loading and decrease in power quality [1]. There is an ongoing effort to handle this issue by various researchers. EV-to-EV charge sharing based solutions are proposed recently to encourage EV owners with excessive charge share/sell their charge with other EV owners in need. Thus, the discharging EVs (DEVs) can serve as a flexible source of energy which can reduce the grid loading due to EV charging. Kamboj et al. [2] discussed how a coalition of several EVs could better represent them in vehicle-to-grid (V2G) systems. However, the work neglects the market perspective for the EVs to sell electricity back to the grid. The authors in [3] recommended that game theory and matching theory are well suited to model and analyse the complex and flexible energy trading and power transfer interactions among the EVs, grid and smart communities. In matching theoretic approaches, sellers and buyers can configure their preferences based on utilities during the process. The problems solved by the matching theory are usually divided into three types: one-to-one matching, one-to-many matching, and many-to-many matching.

1 Introduction

Widespread adoption of electric vehicles (EVs) can have some adverse effects on the grid due to a subsequent increase in loading and decrease in power quality [1]. There is an ongoing effort to handle this issue by various researchers. EV-to-EV charge sharing based solutions are proposed recently to encourage EV owners with excessive charge share/sell their charge with other EV owners in need. Thus, the discharging EVs (DEVs) can serve as a flexible source of energy which can reduce the grid loading due to EV charging. Kamboj et al. [2] discussed how a coalition of several EVs could better represent them in vehicle-to-grid (V2G) systems. However, the work neglects the market perspective for the EVs to sell electricity back to the grid. The authors in [3] recommended that game theory and matching theory are well suited to model and analyse the complex and flexible energy trading and power transfer interactions among the EVs, grid and smart communities. In matching theoretic approaches, sellers and buyers can configure their preferences based on utilities during the process. The problems solved by the matching theory are usually divided into three types: one-to-one matching, one-to-many matching, and many-to-many matching.
The authors in [8] formulated a cooperative game where the merge and the split algorithm is employed to identify the coalition, and the matching technique is applied to identify partnership among charging EV (CEV) and DEV. Moreover, the authors proved that the cooperation benefits both the grid and the EV owners. The benefit of the grid is in terms of the reduced peak-valley difference of power load whereas the EV users are satisfied in less charging cost and higher state-of-charge (SOC).

In another study by Bahrami and Parniani [9] suggested the benefit to the EV owners by developing a stochastic model based on the game-theoretic framework. By this model, individual EVs can decide their charging time to finish their charging process by the desired deadline. The authors in [10], [11] suggested the EV-to-EV charging strategies to reduce the EV charging load burden on the grid. However, designing an adequate and effective online EV-to-EV charging plan remains an open issue.

The authors in [12] modelled EVs to CS interaction as a many-to-one and stable matching whereas the communication among CEVs and DEVs at the same charging station (CS) has been modelled as a many-to-many matching. The authors proved that this framework enhances the reliability of the grid along with the improvement in the quality of experience of EV owners. In [13] a novel algorithm based on matching theory was proposed which fulfils the charging request of EV owner by offering the sufficient supplier for EVs seeking charging service. The authors in [14] proposed three bipartite graph-based max-weight V2V matching algorithms for stable trading among EV providers and consumers to optimise network social welfare. However, [12–14] lacks the provision of the incentive system and participating entities did not get the payoff.

Various researchers have explored the incentive system in cooperative games for transportation architecture. The authors in [15] proposed a cooperation-based incentive system so that messages can be forwarded in a VANET to make end-to-end messaging possible. This system ensured the payoff to be given to each participating node. The concept of an incentive system to those EVs which participated in the car sharing network has been explored in [16]. The authors proposed a game-theoretic framework where EVs with excess energy can trade their energy to charge-deficit EVs. Moreover, the authors utilised the Nash bargaining theory to show that participation in the network can yield profits for the seller driving to their destination. The authors in [17] formulated a multi-agent potential game for a fleet of EVs that converges to a unique Nash equilibrium while optimising system cost and customer payoff. In addition to this, the authors also proved the asymptotical stability of the Nash equilibrium point.

1.2 Motivation

Trading energy from EVs with surplus energy to fulfil the energy demand of CEVs locally is gaining attention nowadays [8, 10–13, 16]. Various researchers suggested that quality of experience to the buyer and seller EVs while trading energy can be achieved through matching theory. The existing literature proposed to merge and split matching [8], stable marriage matching algorithm [12], Max-weight matching [14].

1.2.1 Comparison of Shapley and Shubik [4], Yu et al. [8], Zeng et al. [12], Kim et al. [13], and Zhang et al. [14]: These literature are based on preference-based matching theoretic framework whose objective is to fulfil the charging request of EV owner by offering the DEV as sufficient supplier.

i. In preference based matching it is the choice of suppliers and consumers to whom they wish to match. In this scenario, a profitable matching is there but not only profitable.

ii. Lacks the provision of the incentive system and participating entities did not get payoffs.

These matching algorithms were preference-based algorithm where the participants aware of other participants actions from a ranking. Based on the preference-based ranking, they form coalitions. However, the economic feasibility of the coalition is ignored and every EV participates in the coalition formation. Unlike the previously mentioned algorithm, the proposed scheme is motivated from Shapley and Shubik [4, 5] assignment behavioural game where the participants are unaware of the action profile of other participants and participate in coalition only when the coalition is economically feasible otherwise acts as an independent entity.

1.2.2 Comparison of proposed work with Nax et al. [5]: The proposed scheme is different from [5] in certain aspects mentioned below:

i. There is no randomisation in terms of aspiration rate, which is calculated based on SOC of the EV.

ii. The calculation of charging and discharging price bids by the utilising cost function is included in the proposed work.

iii. The buyer and seller EVs are in the negotiation while making coalitions and every participating EV is equally active. Thus the coalition made using this process is profitable as well as stable.

For charging scheduling problem EV needs to share some information with the CS operator. Hence, there is a need for an efficient communication platform to enable the required information exchange among EVs, CSs, and charging network operators [18]. Apart from this, the communications system is crucial for V2G networks in supporting the bidirectional information exchanges. Recently, typical communications architectures and infrastructures have been proposed [19, 20]. However, for cooperative games, cloud-based communication architecture is widely suggested [21, 22]. In [21] the authors proposed a cloud-based network selection approach where EV owners select a network according to a coalition formation game method. The authors in [22] utilised cloud communication architecture to announce the strategies to coordinate the allocation of transportation and energy resources among EVs. Motivated from [21, 22], this paper adopted a cloud-based architecture for information exchange among seller and buyer EVs and CS. It also adopted a wireless medium of server communication amongst EVs and CS through vehicle smart link (VSL) which is embedded inside the EVs.

1.3 Contribution

The major contributions proposed in this paper are as follows:

i. Fairness in the game: Unlike the existing algorithm in the proposed assignment matching game aspiration level and bids of CEV and DEV is not chosen randomly as it can affect the fairness of the game as some participants might be more active than others. Thus, automated aspiration rate calculation based on the initial SOC is done.

ii. Privacy: Unlike the previous algorithm, there are no preferences, send by CEV and DEV to get matched to the central authority. However, central authority is replaced with a cloud-based application and trading game is a behavioural game where no prior preferences are submitted and players are unaware of the information of others. Moreover, adjustments of aspiration levels will lead to the convergence of the game and there is no need for any integer linear programming to obtain the solution. Thus the privacy of bidders and sellers is preserved.

iii. Numerical analysis and discussion: For the performance evaluation, a single CS with a maximum ten CEVs and ten DEVs at a time has been considered. Matching of these EVs will help in reducing grid dependency and benefit of CS operator across 24 h is increased to 32.31%. Along with this, CEV owners benefitted in terms of reduced cost, whereas DEV owners in terms of increased revenue.

1.4 Organisation

This paper is organised as follows. Section 2 presents the system framework, where the interaction of EVs, cloud server and CS are
depicted. In Section 3, the working of the proposed scheme is discussed. The details of the proposed matching algorithms are elaborated in Section 4. Stability and convergence of the proposed game are discussed in Section 5. Extensive simulations are conducted and discussed in Section 6. A conclusion is drawn in Section 7. Finally, future work is discussed in Section 8.

2 System framework

Fig. 1 depicts the proposed framework with a CS, a connected cloud application hosted on the server and the moving fleet of EVs. These mobile EVs are facilitated with an infrastructure where they can either charge themselves or can discharge themselves. Thus, the ability of EVs to charge and discharge as per their convenience makes them seller and buyer thereby they participate in energy trading in the proposed work. In the proposed framework, the cloud connected application is bridging the gap of information exchange among EVs and the CS. EVs have an inbuilt device known as Vehicle Smart Link (VSL), which is connected to the cloud platform. If an EV does not have this device embedded in the vehicle system, it can be installed externally. VSL of CEV and DEV takes EV owner's input and send the acquired data to the cloud server. At cloud server, matching of EVs seeking to charge and discharge is performed, and the final matched information is notified to the CS. Moreover, the cloud server sends the other EV owners input such as charging power bid, aspiration rate and plug out time to the CS. Further, the CS prepares a bidding schedule and notifies it to the cloud server before the initialisation of the matching process.

3 Working of the proposed scheme

The working of the proposed scheme is elaborated in Fig. 2. The CEV (CEV), activates its charging mode through VSL and gets connected to the cloud-based application. EV owners enter the time they are willing to spend for the vehicle charging. VSL after taking the input calculates \( P_{\text{avg}} \) and calculates the charging bid as per the power requirement per hour and the aspiration rate, which indicates the willingness to pay based on the current SOC of the CEV. The data calculated by the VSL is then transmitted to the cloud server, which processes the data and then transmits back the payment details, acceptance notification and the time it CEV, has to reach the CS. The DEV owners keep its VSL activated in discharging mode and gets discharging requests from the cloud. After accepting the request, they enter the time they are willing to spend for discharging and the final SOC when they leave the CS. In accordance with the discharging request received by the VSL, discharging bid and aspiration rate is calculated and transmitted to the cloud server. After the matching, the DEV is notified regarding the amount it will receive for discharging and the time they need to reach the CS, which is in accordance to the schedule received by the CS before the commencement of the matching algorithm. All charging request and discharging acceptance in 5 km radius are routed to one CS.

The cloud server performs a vital role in this system architecture. It receives the charging requests from the CEV, and broadcasts them to all the DEV with active discharging mode. In the proposed system, it is assumed that all the charging and discharging requests received by the cloud server from VSL in a certain radius are directed to one CS. After taking all inputs from the VSL of all EV owners, it calculates the final bid for all the EVs and DEVs by using the proposed scheme. Using the cooperative game algorithm, it attempts to match the CEVs and DEVs to form coalitions and updates the aspiration levels of all matched and unmatched EVs to make maximum possible coalitions. After the matching, it sends the acceptance notification, price and time of reporting to all the participating EVs as well as the CS. If in case, the cloud has more charging and discharging requests than the EV Supply Equipment (EVSE), the charging and discharging requests are rejected, thus making this algorithm dynamic in nature.

4 Problem formulation

This section presents the matching of charging and discharging requests of the EVs participating in the proposed energy trading game. The main objective of the proposed game is to maximise the social welfare function or in other words, to ensure greater profits to the entities such as CEVs, DEVs and CS participating in this energy trading game. The entire proposed game is shown in Fig. 3 and has been explained using three algorithms.

4.1 Charging vehicle game dynamics

Algorithm 1 (see Fig. 4) focuses on the charging vehicle dynamics. It is assumed that there is \( n \) number of CEVs indexed by \( i \), \( CEV_i = \{1, 2, \ldots , n\} \). The CEV\((i)\) user gives the input for the time of stay \( t_{\text{char}}(i) \) then, the VSL acquires values of the initial SOC \( (SOC_{\text{in}}(i)) \), the capacity of the battery \( (Cap_{\text{batt}}(i)) \) and minimum charge required \( (C_{\text{min}}) \) from the Battery Management System (BMS) and computes the charging rate \( (C_{\text{rate}}(i)) \), power requirement per hour \( (Power_{\text{avg}}(i)) \) as follows:

\[
C_{\text{rate}}(i) = \frac{SOC_{\text{in}}(i) - SOC_{\text{char}}(i)}{t_{\text{char}}(i)}
\]

\[
Power_{\text{avg}}(i) = \frac{C_{\text{rate}}(i) \times Cap_{\text{batt}}(i)}{t_{\text{char}}(i)}
\]

The final SOC \( (SOC_{\text{final}}(i)) \) of CEV\((i)\) is 1. The calculation of price bid \( (P_{\text{bid}}(i)) \) is motivated from [23] where the charging efficiency \( (\eta) \) is assumed to be 0.85.
The aspiration rate of the CEV \(d_{\text{char}}(i)\) has an inverse relation to the initial SOC \(\text{SOC}^\text{in}(j)\), such that when the SOC is lower than the CEV will attempt to lower the payment to be paid for the charging by increasing the \(d_{\text{char}}(i)\) which is calculated as follows:

\[
d_{\text{char}}(i) = \frac{k_1}{\text{SOC}_{\text{char}}(i)}
\]  

The VSL after calculating the values, sends the data tuple of \(\{P_{\text{char}}(i), d_{\text{char}}(i), t_{\text{char}}(i)\}\) to the cloud server. The cloud server after receiving the charging request broadcasts discharging request to the discharging mode active DEVs.

4.2 Discharging vehicle game dynamics

It is assumed that there \(n\) number of DEVs indexed by \(j\), \(\text{DEV}_j = \{1, 2, \ldots, n\}\). Similarly, the DEV user gives the input of time of stay \(t_{\text{dis}}(j)\) and the final desired SOC \(\text{SOC}^\text{fin}(j)\). The VSL of the DEV(j) calculates the charging rate \(D_{\text{rate}}(j)\), power requirement per hour \(\text{Power}_{\text{dis}}^\text{avg}(j)\), price bid \(P_{\text{dis}}(j)\), Aspiration rate \(d_{\text{dis}}(j)\) after acquiring information of the initial SOC \(\text{SOC}^\text{in}(j)\), the capacity of the battery \(\text{Cap}_{\text{dis}}(j)\) from the BMS.

The calculations are as follows:

\[
D_{\text{rate}}(j) = \frac{\text{SOC}^\text{in}(j) - \text{SOC}^\text{fin}(j)}{t_{\text{dis}}(j)}
\]

\[
\text{Power}_{\text{dis}}^\text{avg}(j) = D_{\text{rate}}(j)\times \text{Cap}_{\text{dis}}(j)
\]

\[
P_{\text{dis}}(j) = l_1\times \text{Power}_{\text{dis}}^\text{avg}(j) + l_2
\]

\[
d_{\text{dis}}(j) = k_2\times \text{SOC}_{\text{dis}}(j)
\]
The DEVs then send their data tuple to the cloud server as \[ \{P_{\text{dis}}(i), d_{\text{dis}}(i), t_{\text{dis}}(i)\} \] where they are queued as per their time of arrival. The discharging vehicle dynamics is also illustrated in Algorithm 2 (see Fig. 5).

### 4.3 Cloud application game dynamics

The cloud game dynamics is also discussed in Algorithm 3 (see Fig. 6). The cloud after receiving the charging requests and discharging demands calculates the final bid of the CEVs and DEVs as follows:

1. The cloud after receiving the charging requests and discharging demands calculates the final bid of the CEVs and DEVs as follows:
   
   \[
   \begin{align*}
   P_{\text{final}}^{\text{char}}(i) &= P_{\text{char}}(i) - d_{\text{char}}(i) \\
   P_{\text{final}}^{\text{dis}}(j) &= P_{\text{dis}}(j) + d_{\text{dis}}(j)
   \end{align*}
   \]

Then the charging request of CEV(i) is matched with discharging demand of DEV(j) and gain of their matching is calculated as

\[
\text{gain}_{ij} = (P_{\text{char}}(j) - P_{\text{dis}}(i))
\]

Equation (11) describes the difference between the willingness of the jth DEV to accept if matched with the ith CEV and the willingness of the jth CEV to pay if matched with the ith DEV. Thus, this equation is similar to social welfare function which is defined as the difference between the cost incurred by the buyer and the power generation cost of the seller [24]. Furthermore, the condition of matching is given in (12), which will ensure that the CEV and DEV will match only if the gain is more than the minimum pay off which CEV and DEV can pay. Hence, (12) is ensuring to get social welfare maximised

\[
\text{gain}_{ij} > d_{\text{char}}(i) + d_{\text{dis}}(j)
\]

and aspiration rates are modified as

\[
\begin{align*}
\pi_{ij} &= \frac{P_{\text{final}}^{\text{char}}(i) + P_{\text{final}}^{\text{dis}}(j)}{2} \\
\end{align*}
\]

Matrix \( A_{n,m} \) is denoted as the assignment matrix which assigns 1 for matching and 0 when not matched. Matrix \( f_{\text{price},c,m} \) is used to represent the prices for all the possible assignments. The assignment matrix is updated as \( A_{ij} = 1 \) and the price matrix is updated as \( f_{\text{price}}_{ij} = \pi_{ij} \). The matrix operation is done as follows:

\[
A_{ij} = \begin{cases} 
1, & \text{if the } i\text{th CEV and the } j\text{th DEV is matched} \\
0, & \text{if the } i\text{th CEV and the } j\text{th DEV is unmatched}
\end{cases}
\]

\[
f_{\text{price}}_{ij} = \begin{cases} 
\pi_{ij}, & \text{if the } i\text{th CEV and the } j\text{th DEV is matched} \\
0, & \text{if the } i\text{th CEV and the } j\text{th DEV is unmatched}
\end{cases}
\]

If (12) and (13) are not fulfilled, then the CEV(i) is matched with the next queued discharging request and the unpaired CEV(i) and DEV(j) reduce their aspiration rates as follows:

\[
\begin{align*}
\pi_{\text{updated}}^{\text{char}}(i) &= \pi_{\text{char}}(i) - X \\
\pi_{\text{updated}}^{\text{dis}}(j) &= \pi_{\text{dis}}(j) - X
\end{align*}
\]

Fig. 5 Algorithm 2: steps for discharging vehicle game dynamics

**Input:** \( P_{\text{char}}, P_{\text{dis}}, d_{\text{char}}, \text{ and } d_{\text{dis}} \)

1. Accept charging price bids \( P_{\text{char}} \), discharging price bid \( P_{\text{dis}} \), aspiration rate \( d_{\text{char}} \), aspiration rate \( d_{\text{dis}} \) which are queued on the basis of time of arrival.
2. The final charging bids of charging EV \( P_{\text{final}}^{\text{char}} \), and discharging EV \( P_{\text{final}}^{\text{dis}} \) are computed.
3. Charging EV encounters discharging EV and matching gain is computed.
4. if the match satisfies the profit formula then
   5. \( A_{n,m} = 1 \)
   6. else if the match doesn’t forms
   7. \( A_{n,m} = 0 \)
8. while all \( d_{\text{dis}} \) and \( d_{\text{char}} \) > 0 do
9. if a match of charging EV and discharging EV is formed then
10. price governing \( f_{\text{price}} = \frac{P_{\text{final}}^{\text{char}}(i) + P_{\text{final}}^{\text{dis}}(j)}{2} \) is updated in \( a(i,j) \) and \( A(i,j) = 1 \) and aspiration rates are updated as:
11. \( d_{\text{dis}}(i+1) = P_{\text{char}} - f_{\text{price}} \)
12. \( d_{\text{char}}(i+1) = P_{\text{dis}} - f_{\text{price}} \)
13. else if match is already paired, aspiration rate remains unchanged then
14. the aspiration rates of charging EV and discharging EV are reduced by a common factor \( X \) and \( a(i,j) \) and \( A(i,j) \) remains zero.
15. The final payment \( (p_{\text{pay}}) \) and revenue \( (r_{\text{rev}}) \) calculated using (19) and (20) respectively and the schedule details are sent to charging EVs and discharging EVs.
16. Bidding information are accepted for the next hour and the matching resumes after one hour.

Fig. 6 Algorithm 3: steps for cloud application game dynamics

where \( X \) is a real number.

After all the possible CEVs and DEVs are matched, the price paid by CEVs and the revenue earned by the DEVs are calculated using the following equations:

\[
\begin{align*}
\text{pay}_i &= \begin{cases} 
  x_1 f_{\text{price}} + y + \text{Part} + \text{misc}, & \text{if } x_1 < x_2 \\
  x_2 f_{\text{price}} - y + \text{Part} + \text{misc}, & \text{if } x_1 > x_2
\end{cases} \\
\text{rev}_j &= \begin{cases} 
  x_1 f_{\text{price}} + y - \text{Part} + r_c, & \text{if } x_1 < x_2 \\
  x_2 f_{\text{price}} - \text{Part} + r_c, & \text{if } x_1 > x_2
\end{cases}
\end{align*}
\]

where \( x_1 \) Power_{avg}(j), \( x_2 \) Power_{avg}(i), \( y \) (Power_{avg}(j) - Power_{avg}(i))*GridPrice(t), \text{Part} Participation cost, \text{misc} Miscellaneous cost and \( r_c \) reward for DEVs that participate in the coalition.
The final payment by CEVs ($pay_i$) and revenue earned by DEVs ($rev_j$) is notified to the respective EVs along with the time they need to reach the CS.

5 Stability and convergence of the proposed game

5.1 Optimality

An assignment $A_{n,m}$ is optimal if

$$\sum_{(i,j) \in CEV \times DEV} A_{ij} \times gain_{ij} = \nu(\mathbb{N})$$

where $\nu(\mathbb{N})$ is the value of an optimal assignment.

5.2 Pairwise stability

Aspiration rates $d_{char}^{updated}$ and $d_{dis}^{updated}$ are pairwise stable if $\forall CEV(i)$ and $DEV(j)$ with $A_{ij} = 1$, $P_{char}^{final}(i) = P_{dis}^{final}(j)$, and $P_{char}^{final}(i) < P_{dis}^{final}(j)$ for every alternative CEV $i'$ and $P_{dis}^{final}(j) < P_{char}^{final}(i)$ for every alternative DEV $j'$.  

5.3 Core

The stability and convergence of the proposed game is the core. The core is when $A_{n,m}$ is optimal and $d_{char}^{updated}$ and $d_{dis}^{updated}$ is pairwise stable.

**Remark 1:** The aspiration rate of CEV ($d_{char}$) and DEV ($d_{dis}$) should always be positive. If the aspiration rate of any EVs is negative, that will imply that the DEV’s is eager to pay charges for discharging and CEVs will earn money for charging their vehicles. In that case, there will be a change in strategy profile which has been proposed and the core will be disturbed. Thus, there will be no coalitions satisfying the optimality condition shown in (12) and all the EVs will be charging independently, which is uneconomical and will disturb the stability of the core.

6 Numerical simulations

This section highlights the simulations and results to evaluate the proposed scheme. For performance evaluation, a single CS with a maximum of 20 EVs at a time has been assumed. The battery capacity of these EVs is considered to be 16, 24 and 32 kWh. The CS accepts a maximum of ten charging and discharging price bids within a granularity of 1 h time frame. Various simulation parameters and grid pricing are shown in Tables 1 and 2, respectively.

6.1 Calculation of bid vector

The calculation of charging and discharging bid is the most integral part of the proposed energy trading game. The charging price bid calculation is an integral step to find suitable coalition, which improves the social welfare function of the participating entities. The price vector of the CEVs and DEVs is calculated using (3) and (7), respectively. The charging bid profile of ten CEVs throughout 24 h is presented in Fig. 7a and discharging bid profile of ten DEVs throughout 24 h is presented in Fig. 7b. For improved clarity, the charging price bid vector of of 24 h at eighth charging EVSE is shown in Fig. 8a. Similarly, discharging bid vector of 24 h at eighth discharging EVSE is shown in Fig. 8b. It can be seen that all discharging bids received at eighth discharging EVSE are greater than the charging bids received on the eighth charging EVSE, which is one of the vital criteria for finding coalition pairs in this proposed game. Moreover, the price bid of CEVs and DEVs at 0600 h is shown in Figs. 9a and b. Here also, it can be clearly visualised that the discharging bid vector always remains higher than the charging bid vector at every instance.

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**Table 1** Grid price (in Rs/kWh)

| Time         | Price, Rs./kWh |
|--------------|----------------|
| 0000–0600    | 2.304          |
| 0600–0900    | 2.413          |
| 0900–1200    | 2.465          |
| 1200–1500    | 2.421          |
| 1500–1800    | 4.421          |
| 1800–2400    | 3.884          |

**Table 2** Simulation parameters

| Parameter | Values |
|-----------|--------|
| $\eta$    | 0.85   |
| $c$       | 0.1    |
| $l_1$     | 2      |
| $l_2$     | 1      |
| $k_1$     | 0.25   |
| $k_2$     | 0.0025 |
| $X$       | 0.2    |
| $Part$    | 2.28   |
| Misc      | 3.472  |
| $r_e$     | 10     |
| $r_i$     | 5      |

**Fig. 7** Price bid of CEV and DEVs

(a) Price bid of CEVs, (b) Price bid of DEVs

The payment by CEVs when they charge independently and revenue earned by DEVs when they operate independently is given by (23) and (24), respectively

$$pay_i = Power_{char}^{avg}(i) \times Grid\ Price(t) + Part + misc$$

$$rev_j = Power_{dis}^{avg}(j) \times Grid\ Price(t) - Part + r_i$$
6.2 Optimal matching

This section highlights about how the algorithm has been used to obtain optimal matching. One of the stability criteria of convergence of this game is $P_{\text{dis}}^{\text{final}}$ is greater than $P_{\text{char}}^{\text{final}}$ which is clearly depicted in Table 3. In addition to this, Tables 4 and 5, which depicts the sum of aspiration level of CEV’s and DEV’s and the gain of the corresponding EV’s. From the tables, it can be seen from the highlighted text that during the 24th hour, the 5th CEV forms a match with the 1st DEV and the sum of the aspiration rate is $-1.24$, whereas the gain is $13.45$ which satisfies the conditioned mentioned in 12. Similarly, the 6th CEV forms a match with the 7th DEV with the sum of $-1.45$ and the gain of $0.86$.

6.3 Reduction of grid dependency

In Fig. 10, it can be seen that by utilising the excess power of DEV’s in the algorithm, the power required to meet the load demand in a CS is reduced significantly. In the 0400 h, it can be seen from the highlighted text that during the 24th hour, the 5th CEV forms a match with the 1st DEV and the sum of the aspiration rate is $-1.24$, whereas the gain is $13.45$ which satisfies the conditioned mentioned in 12. Similarly, the 6th CEV forms a match with the 7th DEV with the sum of $-1.45$ and the gain of $0.86$. 

### Table 3
Illustration of $P_{\text{char}}^{\text{final}}$ and $P_{\text{dis}}^{\text{final}}$ at the 24th hour

|              | $P_{\text{char}}^{\text{final}}$ | $P_{\text{dis}}^{\text{final}}$ |
|--------------|-----------------------------------|----------------------------------|
| CEV1         | -0.4778                           | DEV1                             |
|              | 14.762                            |                                  |
| CEV2         | 0.2937                            | DEV2                             |
|              | 11.0817                           |                                  |
| CEV3         | -1.9792                           | DEV3                             |
|              | 15.7211                           |                                  |
| CEV4         | 0.2978                            | DEV4                             |
|              | 10.2817                           |                                  |
| CEV5         | 0.5515                            | DEV5                             |
|              | 5.801                             |                                  |
| CEV6         | -1.9792                           | DEV6                             |
|              | 10.6021                           |                                  |
| CEV7         | 0.6673                            | DEV7                             |
|              | 3.8812                            |                                  |
| CEV8         | 0.6109                            | DEV8                             |
|              | 5.8009                            |                                  |
| CEV9         | -1.9792                           | DEV9                             |
|              | 13.8011                           |                                  |
| CEV10        | 0.621                             | DEV10                            |
|              | 5.8                               |                                  |

### Table 4
Sum of aspiration level matrix of CEV and DEV at the 24th hour

|         | DEV 1 | DEV 2 | DEV 3 | DEV 4 | DEV 5 | DEV 6 | DEV 7 | DEV 8 | DEV 9 | DEV 10 |
|---------|-------|-------|-------|-------|-------|-------|-------|-------|-------|--------|
| CEV1    | 2.50  | 2.00  | 0.69  | 4.50  | 0.69  | 0.26  | 4.50  | 0.07  | 0.16  | 4.50   |
| CEV2    | 0.69  | -0.86 | -1.36 | 4.00  | 0.19  | -0.24 | 4.00  | -0.43 | -0.34 | 4.00   |
| CEV3    | 4.00  | -1.36 | -1.36 | -1.86 | -0.31 | -0.74 | 3.50  | -0.93 | -0.84 | 3.50   |
| CEV4    | -0.31 | -1.86 | -1.86 | -1.86 | -2.36 | -1.24 | 3.00  | -1.43 | -1.34 | 3.00   |
| CEV5    | 1.24  | -2.36 | -2.36 | -2.36 | -2.36 | -2.86 | 2.50  | -1.93 | -1.84 | 2.50   |
| CEV6    | 2.50  | -2.86 | -2.86 | -2.86 | -2.86 | -0.95 | -1.45 | -0.50 | -2.34 | 2.00   |
| CEV7    | -2.43 | -3.36 | -3.36 | -3.36 | -2.86 | -3.36 | -2.86 | -1.08 | -2.84 | 1.50   |
| CEV8    | -2.84 | -3.86 | -3.86 | -3.86 | -3.86 | -3.86 | -2.86 | -1.61 | -2.11 | 1.00   |
| CEV9    | 1.00  | -4.36 | -4.36 | -4.36 | -4.36 | -4.36 | -2.45 | -2.86 | -3.41 | -1.50  |
| CEV10   | -3.86 | -4.86 | -4.86 | -4.86 | -3.86 | -3.86 | -4.86 | -2.11 | -4.86 | -4.86  |
the total requirement is of 70.72 kW. Thus about 48.32 kW of power is taken from the grid during 0400 h. Here the load demand of the CS consists of the load of CEVs and an additional 15 kW of energy which is used to fulfill the basic power requirements of CS such as air-conditioning, lightning, transformer operation and so on. Thus DEVs can be considered as a source of energy for CS and can be used to reduce the grid overloading by providing suitable revenue to the DEV owners. Moreover, the charging demand and the discharging power available throughout 24 h are shown in Fig. 10b. Here two cases can be identified.

6.3.1 When charging power greater than discharging power: Here the coalition amongst the CEV and DEV is formed and there is a combination of V2G and G2V technology. At 1200 h, the charging power required is 56.68 kW and the discharged power available is 32.03 kW. Thus G2V power is 24.65 kW and V2G power is 32.03 kW.

6.3.2 When charging power less than discharging power: The coalitions are formed and the power requirement is fulfilled by V2G technology only. At 0800 h, the power from DEVs or V2G is 55.35 kW and power required for charging is 51.02 kW. Thus the entire power requirement is fulfilled by the V2G and the excess power of 4.33 kW can be sold to the grid by the CS or can be stored.

6.4 Dynamic nature of the game

This subsection highlights the importance of the proposed algorithm in handling the mobility of EVs. It can be illustrated in Figs. 11a and b for the CEVs and DEVs, respectively. Fig. 11 highlights the Crate and Drate patterns calculated using (1) and (5), respectively, of three EVSEs in which different EVs are plugged in across 24 h. The charging rate remains constant until the time EV owners wish to stay at the CS. When the time mentioned by the EV owners gets completed, that particular EV leaves the CS, and the next queued bid received by cloud server takes its place. Here, at the first EVSE an EV is connected for two hours at a Crate of 0.35 then another EV arrives, and it is connected for a 2 h at a Crate of 0.39. Similarly, at the second EVSE, the initial Crate is of 0.225 and after, 4 h the Crate is replaced by 0.1. For the third EVSE in Fig. 11b, an EV discharge at a Crate of 0.133 for 3 h, which is then replaced by another discharging EV which discharges at a Crate of 0.33. Thus, the dynamic nature of the game is maintained by the proposed game.

6.5 Comparison of profit analysis with and without proposed algorithm

This subsection presents the effect of coalition formation on profits earned by CS, CEV and DEV. For instance, in Fig. 12a at 0900 h, there is almost a zero profit without coalition between CEVs and DEVs and in contrast a profit of 100 Rs with the proposed coalition game. However, there are few instances where the profit earned is more in the case of other algorithm. For example, after 1700 h, it
can be seen that the profit revenue earned by the CS is greater when charging is conducted independently. During these hours, the grid prices are the highest due to high loading and as being a behavioural game, the DEVs tend to discharge a higher percentage of their power at a higher bid to earn more revenue. In this case, it can be seen that at 2100 h, the CS suffers a loss of 40 Rs. However, Table 6 clearly illustrates that the proposed game is profitable throughout the 24 h framework.

Apart from the profit earned by the CS, the proposed algorithm provides benefit to EV owners as well. This can be justified in Figs. 12b and c. As shown in Fig. 12b, the payment paid by the CEVs is less when they participate in the proposed algorithm in comparison to the amount spent when they charge their vehicles independently. For instance, the payment by the tenth EV when it charges vehicle independently pays for Rs. 19.77, whereas the payment by the tenth EV when it participates in the proposed algorithm pays a lesser amount of Rs. 12.58. Thus a profit of Rs. 7.19.

On the same line, the revenue received by the DEVs is higher when they participate in the coalition than when they discharge their EVs without participating in the coalition. For instance, the revenue earned by the fourth EV when it participates independently is Rs. 19.31, whereas when it participates in the proposed algorithm the revenue earned is Rs. 23.89, making a profit of Rs. 4.58. Thus, all the entities participating get better returns in most of the cases when they use the proposed game in comparison to the returns they get when they function independently.

7 Conclusion

In this paper, a behavioural energy trading game for DEV and CEV has been developed so that EVs exchange energy amongst them to get payoffs and CS operator also get benefited. The main findings of the proposed work are that a cloud-based application acts as a matchmaker between DEV and CEV and replaces the central authority. Moreover, the behavioural nature of the game replaces the need of complex integer linear programming solutions to be executed and convergence of the game to the core is discovered by a sequence of adjustments of aspiration level. The significant advantages of this game are that it reduces the grid dependency and improves the profit of operation of DEVs. The profit revenue earned by a CS across 24 h when CEVs and DEVs participate in the proposed game is 32.31% more than the case when they did not get involved. Moreover, the DEVs get higher revenue on discharging, and the CEVs get a low charging cost when participating in a cooperative game. The use of VSL reduces the involvement of EV owners in decision making and thus makes the process autonomous while maintaining the profit interests. Moreover, an aggregation cloud server, which accepts requests from EVs and notifies the acceptance or rejections of their requests. Thus, making the system decentralised and dynamic.

8 Future work

To support this type of architecture which has been discussed in this paper, special attention is required to improve the CS architecture as well as the communication systems which plays a very vital role. The Cloud Server should be lag free and should work efficiently. The power provided at the CS should maintain optimum quality. Moreover, further work will consider the scenario when the CEV and DEV could not reach on the agreed time. Thus, all the discussed factors will serve as future work.

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Table 6 Profit revenue of CS for 24 h time-frame

| Without coalition, Rs. | With coalition, Rs. |
|----------------------|-------------------|
| 1408.3               | 2080.4            |

Fig. 12 Comparison with and without proposed algorithm

(a) Profit of CS, (b) Payment of CEVs for the first hour, (c) Revenue of DEVs for the first hour.

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