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Game-theoretic energy trading network topology control for electric vehicles in mobile smart grid

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Abstract: Existing works on energy trading consider different schemes for forming energy trading networks, which assume that each plug-in hybrid electric vehicle (PHEV) is connected with a single micro-grid. Consequently, in on-peak hours, a PHEV obtains the requested energy during the allotted time slot by paying a higher price. Alternatively, the PHEV waits for a significant duration of time to get serviced until the on-peak hour elapses. In this study, the authors propose that a PHEV may obtain energy from any of the available micro-grids within a coalition instantaneously without paying higher price. In this work, the problem of energy trading network topology control (ENTRANT) for PHEVs is studied as a 'multi-leader multi-follower Stackelberg game'. In this game, each PHEV acts as a leader, and decides the amount of energy to be requested to the selected micro-grid. On the other hand, the micro-grids act as followers, need to decide the price per unit energy. Using variational inequality, it is shown that the proposed scheme, ENTRANT, has generalised Nash equilibrium, which is also socially optimal. ENTRANT enables the PHEVs and the micro-grids within a coalition to reach the equilibrium state, is evaluated theoretically, as well as through simulations.

1 Introduction

The traditional electrical grids with advanced techniques, termed as 'smart grid', are envisioned to achieve high reliability of the energy trading networks. A smart grid [1–3] is visualised to be a cyber-physical system, which is highly efficient and robust in nature, equipped with sustainable models of energy production, distribution and usage. Smart grid integrates several advanced mechanisms such as use of advanced metering infrastructure [4], automated meter reading [4], smart meter (SM), data aggregation unit, meter data management system (MDMS), distributed energy resources, energy management systems [5], intelligent electronic devices and plug-in hybrid electrical vehicles (PHEVs) [6], in an electrical grid. In traditional energy trading networks, the energy is distributed unidirectionally to the residential customers by the centralised main grid, and the customers pay an amount decided by the energy service provider after a fixed duration. However, in smart grid having duplex communication infrastructure, the modernised energy trading network has bidirectional electricity exchange facility. The large-scale energy trading network in a smart grid is divided into several micro-grids, which can either supply energy directly to the customers and the PHEVs, or exchange energy with the main grid through the substations. In the presence of several micro-grids, it is desired that each micro-grid serves a small geographical area, that is, a group of customers, to relax the load on the main grid. One of the important features in smart grid is distributed energy management, in which each customer or PHEV can demand energy according to its requirement, and also can schedule appliances depending on his/her/its preferences.

1.1 Motivation

In a smart grid, the concept of green energy generation using renewable-energy resources, that is, reducing CO_2 emission in the environment for energy generation, is prioritised. The micro-grids generate energy typically based on renewable-energy resources. Therefore the amount of energy generated by each micro-grid is not fixed for each time-slot. As a result, the customers and the PHEVs, that is, consumers, either have to pay higher price per unit energy or will have to wait for a certain time duration. If the energy requested by the consumers is higher than the amount of energy generated, the consumers can obtain energy by paying high. In that case, the micro-grid requests other micro-grids having excess amount of energy to serve the demand. Otherwise, the consumers wait for a certain time duration to obtain the energy-service, while paying less. On the other hand, if the micro-grids have excess amount of generated energy, it can supply that excess amount either to the other micro-grids having demand of energy or to the main grid through the substations. Therefore the energy loss through transmission line is higher. Moreover, according to the existing literature, the PHEVs are connected with a single micro-grid. Therefore each PHEV has to either pay high amount per unit energy or has to wait for certain time duration to obtain the energy services. Therefore we propose an energy trading network topology control (ENTRANT) scheme for PHEVs. In this scheme, we consider that each PHEV has the option to request the amount of required energy to any of the available micro-grids. Hence, the PHEVs do not have to wait to obtain the energy service. On the other hand, to obtain the required amount of energy, the PHEVs do not have to pay high. Therefore using the proposed ENTRANT scheme, the PHEVs obtain higher satisfaction by consuming the required amount of energy, whereas the available micro-grids in the coalition ensure better quality of energy service (QoS). Hence, using the proposed scheme, the loss through the transmission line gets reduced and the micro-grids having excess energy obtain higher revenue by supplying the excess amount of generated energy.

1.2 Contribution

In this paper, we propose a non-cooperative ENTRANT scheme for mobile PHEVs in smart grid. We use a multi-leader multi-follower non-cooperative Stackelberg game [7] in the proposed scheme, ENTRANT, to estimate the amount of energy to be consumed by the PHEVs and price per unit energy to be charged by the micro-grids. Using ENTRANT, the PHEVs consume higher amount energy, that is, the satisfaction factor after consuming energy is high, while paying less price per unit energy. On the other hand, the micro-grids utilise the amount of generated energy properly, while ensuring higher revenue by selling the excess amount of generated energy to the PHEVs after satisfying the demand of the customers. We summarise the 'contributions' of this paper as follows:

(i) We propose a game-theoretic ENTRANT scheme, that is, ENTRANT, for proper distribution of generated energy, while ensuring the revenue maximisation of the micro-grids.
(ii) We formulate the interaction between the micro-grids and the PHEVs as a multi-leader multi-follower Stackelberg game. This game model establishes the broader aspect for energy trading network in mobile smart grid.
(iii) We present an algorithm for maintaining the energy trading network in mobile smart grid using the proposed scheme, ENTRANT. The PHEVs decide the amount of energy to be consumed based on the amount of energy required for satisfying the requirement. On the other hand, the micro-grids decide the price per unit energy, while ensuring the proper utilisation of generated energy and the revenue by supplying the requested amount of energy by the PHEVs.

The remainder of the paper is organised as follows. Section 2 summarises the related work in the area of energy management in smart grid. The system model is discussed in Section 3. The proposed scheme, ENTRANT, is described in Section 4. Section 5 depicts the simulation setup and performance evaluation of the proposed scheme, ENTRANT, considering different performance metrics. Finally, Section 6 concludes the paper by citing directions for future work.

2 Related work

In the last few years, lot of research work on smart grid emerged, namely [8–31]. Some of the existing literatures are discussed in this section. Saad *et al.* [8] formulated a coalition game having multiple micro-grids and proposed a distributed algorithm for forming the coalition. Saad *et al.* [8] assumed that one micro-grid can exchange excess energy with the main grid. They did not consider any scheduling approach for distributing the generated energy properly, while satisfying the energy demand of the customers. In case of power exchange between the micro-grid and the main grid, there may be loss of energy over the distribution line. They formulated the utility of micro-grid i by taking into account the loss of energy, as follows [8]

$$U(i) = -w_i P_{i0}^{\text{loss}} \tag{1}$$

Misra *et al.* [10] suggested a distributed dynamic pricing mechanism for charging PHEVs. They used two different pricing schemes namely home pricing and roaming pricing. Such and Hill [12] proposed that efficient and economic operation of an electric energy distribution system can be improved with the implementation of wind generation and storage devices. In such a scenario, they proposed that, if in a certain geographical area, there are some storage devices and some wind generation, which are controllable by the micro-grid, the micro-grid decides whether or not to use these. The rate of variation of wind power is also controlled to have smooth energy supply to the customers. Mondal and Misra [14] proposed a decision making process to form coalitions dynamically between micro-grids and customers.

Bakker *et al.* [15] recommended a distributed load management scheme with dynamic pricing and have modeled it as a network congestion game. Nash equilibrium is presented in order to have an optimal solution. However, in this scenario, if the customer requires more energy in a certain time, then s/he has to wait for some time until the distributed generation can manage it, as the customer does not have the option to switch to another micro-grid and fulfill his/her requirement from that micro-grid. Molderink *et al.* [16] proposed an algorithm by using the energy in the off-peak and the on-peak hours, with a virtual power plant, for energy management. Additionally, they showed that the renewable energy sources are useful to achieve cost effective and environment-friendly energy supply to the end users.

Vytelingum *et al.* [17, 18] proposed an algorithm, in which the customers choose their strategies based on their advance knowledge about the market. The authors discussed about storage devices and benefits from micro-storage implementation. Sanseverino *et al.* [21] studied an algorithm for load shifting and storage device management. The authors proposed that during peak-hour, heavy loads should be turned off and vice-versa. They compared the control mechanism with real storage devices to show the impact of the load shifting scheme on the smart grid. However, in this scenario, if the customer does not want any delay in receiving the requested energy, s/he has to pay high price for it. Fang *et al.* [26] proposed different energy management schemes. However, in their work, new opportunities for improved residential energy management and bill reduction are studied without considering the impact of stochastic scheduling approach for distributed energy management. Erol-Kantarci and Mouftah [32] proposed a time-to-use aware-energy management scheme. In their proposed scheme, a customer consumes energy according to the time, whether it is an on-peak hour or an off-peak hour. If it is an on-peak hour, the customer waits for being served. Otherwise, the customer demands the

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required energy without waiting, if the delay is greater than the maximum allowable delay which is a local variable to the customer. Yet, the energy management policy adopted by the customers and the micro-grids need further research to have an optimal solution and with minimum delay and less message overhead.

In contrast to the existing work, a game theoretic ENTRANT scheme is proposed for the PHEVs functioning in a mobile smart grid environment. We use a non-cooperative multi-leader multi-follower Stackelberg game theoretic approach to develop an optimal solution of energy trading network topology in mobile smart grid.

3 System model

We consider an energy trading network in smart grid consisting of multiple micro-grids and several 'consumers'. The consumers, that is, the customers and the PHEVs, may request for energy service to any micro-grid from the set of available micro-grids in a coalition [14]. After meeting the energy requirements of the customers connected to the micro-grids, each micro-grid decides to sell the excess amount of generated energy to the PHEVs, which are available in the coalition at that time instant in mobile smart grid. The schematic diagram of the energy trading network for mobile smart grid environment is shown in Fig. 1. We consider that each micro-grid has a communicating device, that is, MDMS. With the help of MDMS, each micro-grid sends information to the data aggregation points (DAPs) using wide area network. Each DAP communicates with the SMs, which are associated with the consumers, that is, the customers and the PHEVs, using neighbourhood area network. The appliances at the consumer-end send their energy-consumption informations to the SMs using home area network. The list of symbols considered in this paper is shown in Table 1.

We consider that at each time slot $t \in \mathcal{T}$, where $\mathcal{T}$ is the set of time slots in a day, in a coalition, each consumer $n \in \mathcal{N}(t)$, where $\mathcal{N}(t)$ is the set of the consumers at time slot t, consumes $d_n(t)$ amount of energy. At each time slot $t \in \mathcal{T}$, the set of consumers, $\mathcal{N}(t)$, is combination of the set of customers, $\mathcal{N}^c(t)$, who are static in nature and the set of PHEVs, $\mathcal{N}^p(t)$, which are mobile in nature. Mathematically

$$\mathcal{N}(\cdot) = \mathcal{N}^c(\cdot) \cup \mathcal{N}^p(\cdot) \tag{2}$$

We consider that at time slot $t \in \mathcal{T}$, each micro-grid $m \in \mathcal{M}$, where $\mathcal{M}$ is the set of micro-grids in the coalition, generates $\mathcal{G}_m(t)$ amount of energy. After meeting the energy demand of the set of connected customers, $\mathcal{N}^c_m(t)$, that is, $\mathcal{C}_m(t)$, each micro-grid m has $\mathcal{E}x_m(t)$ amount of excess energy, as shown below

$$\mathcal{E}x_m(\cdot) = \mathcal{G}_{\mathrm{m}}(\cdot) - \mathcal{C}_m(\cdot) \tag{3}$$

where $\mathcal{C}_m(\cdot) = \sum_{n \in \mathcal{N}^c_m(\cdot)} d^c_n(\cdot)$, $\mathcal{N}^c_m(\cdot) \subseteq \mathcal{N}^c(\cdot)$ and $d^{(n)}_c(\cdot)$ is the amount of energy requested by each customer $n \in \mathcal{N}^c_m(\cdot)$. The excess amount of generated energy by each micro-grid m, that is, $\mathcal{E}x_m(\cdot)$, must satisfy the following constraint

$$\mathcal{E}x_m(\cdot) \geq 0, \quad \forall m \in \mathcal{M} \tag{4}$$

The amount of excess energy generated by each micro-grid $m \in \mathcal{M}$, that is, $\mathcal{E}x_m(\cdot)$, is used for serving a subset of the available PHEVs, $\mathcal{N}^p(\cdot)$, that is, $\mathcal{N}^p_m(\cdot)$, in the coalition. Mathematically

$$\mathcal{N}^p_m(\cdot) \subseteq \mathcal{N}^p(\cdot) \tag{5}$$

Each PHEV $n \in \mathcal{N}^p(\cdot)$ has a requirement of d^p_n amount of energy. To fulfill the energy requirement, each PHEV n chooses a micro-grid m having $\mathcal{E}x_m(\cdot)$ amount of generated energy. Therefore the total amount of energy requested to each micro-grid m by the PHEVs $\mathcal{N}^p_m(\cdot)$, where $\mathcal{N}^p_m(\cdot)$ is the set of PHEVs demanded energy from micro-grid $m \in \mathcal{M}$ and $\mathcal{N}^p_m(\cdot) \subseteq \mathcal{N}^p(\cdot)$, must satisfy the following constraint

$$\mathcal{E}x_m(\cdot) \geq \sum_{n=1}^{n \in \mathcal{N}^p_m(\cdot)} d^p_n(\cdot) \tag{6}$$

On the other hand, based on the total demanded amount of energy, each micro-grid $m \in \mathcal{M}$ decides the 'price coefficient', $p_m(\cdot)$, that is, the multiplying factor of the price per unit energy to be paid by the set of connected PHEVs, $\mathcal{N}^p_m(\cdot)$. The price coefficient of each micro-grid m, that is, $p_m(\cdot)$, is defined in Definition 1.

Definition 1: The price coefficient of each micro-grid m, that is, $p_m(\cdot)$, is a function of the ratio of the amount of energy requested to micro-grid m, that is, $\sum_{n=1}^{n \in \mathcal{N}^p_m(\cdot)} d^p_n(\cdot)$ and the excess amount of generated energy by micro-grid m, that is, $\mathcal{E}x_m(\cdot)$. Mathematically

$$p_m(\cdot) = f\left(\sum_{n=1}^{n \in \mathcal{N}^p_m(\cdot)} \tilde{d}^p_n(\cdot), \mathcal{E}x_m(\cdot)\right) = \frac{\sum_{n=1}^{n \in \mathcal{N}^p_m(\cdot)} \tilde{d}^p_n(\cdot)}{\mathcal{E}x_m(\cdot)} \tag{7}$$

With the increase in the number of connected PHEVs with micro-grid m, the amount of energy requested to micro-grid m increases. Hence, the price coefficient increases. On the other hand, the QoS provided by the micro-grids decreases with the increase in the amount of requested energy by the

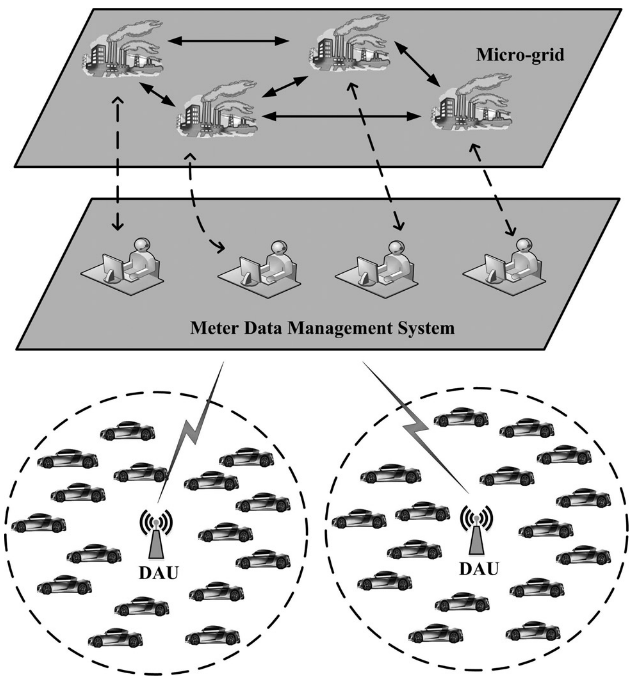

Fig. 1 *Schematic diagram of energy trading network*

ReqMsgType	PHEV_ID	ReqEnergy	FinalSelectFlag
1 byte	4 byte	2 byte	1 byte

a

AckMsgType	MG_ID	Price	AckFlag
1 byte	4 byte	2 byte	1 byte

b

Fig. 2 *Message formats using ENTRANT scheme*
a Request message format
b Reply message format

PHEVs. The 'satisfaction factor' of the micro-grid m, that is, $s_m(\cdot)$, also increases with the decrease in the remaining amount of generated energy. We define the satisfaction factor of micro-grid $m \in \mathcal{M}$ in Definition 2.

Definition 2: The satisfaction factor of micro-grid $m \in \mathcal{M}$, $s_m(\cdot)$, is defined by the ratio of remaining amount of excess energy, that is, $\mathcal{E}x_m^{\text{res}}(\cdot)$ and the excess amount of generated energy after fulfilling the energy demand of the customers, $\mathcal{N}_m^c(\cdot)$, that is, $\mathcal{E}x_m(\cdot)$. Mathematically

$$\begin{aligned} s_m(\cdot) &= \frac{\mathcal{E}x_m^{\text{res}}(\cdot)}{\mathcal{E}x_m(\cdot)} \\ &= \frac{\mathcal{E}x_m(\cdot) - \sum_{n=1}^{n \in \mathcal{N}_m^p(\cdot)} d_n^p(\cdot)}{\mathcal{E}x_m(\cdot)} \\ &= 1 - \frac{\sum_{n=1}^{n \in \mathcal{N}_m^p(\cdot)} d_n^p(\cdot)}{\mathcal{E}x_m(\cdot)} \end{aligned} \tag{8}$$

3.1 Mobility model for mobile smart grid environment

We assume that the PHEVs follow the mobility pattern of Gauss–Markov mobility model [10, 33]. According to the mobility model, each PHEV n updates its location periodically, after crossing a threshold distance. The position and the velocity are considered to be correlated with time, that is, the position of each PHEV n at time instant τ depends on the location and velocity of the PHEV at previous time instant $(\tau - 1)$. We consider that the PHEVs move in a two-dimensional plane. Hence, the Gauss–Markov mobility model is represented as [33]

$$\boldsymbol{v}_n(\tau) = v_n^x(\tau)\hat{i} + v_n^y(\tau)\hat{j} \tag{9}$$

where $v_n^x(\cdot)$ and $v_n^y(\cdot)$ are the velocity components of each PHEV n towards $\boldsymbol{x}$ and $\boldsymbol{y}$ direction. We define $\boldsymbol{v}_n(\tau)$ as follows

$$\boldsymbol{v}_n(\tau) = \alpha v_n(\tau - 1) + (1 - \alpha)\mu + \sigma\sqrt{1 - \alpha^2}\mathcal{W}(\tau - 1) \tag{10}$$

where $\boldsymbol{v}_n(\tau)$ denotes the velocity vector of PHEV n at time τ, α is the variance over time, μ signifies the mean of the velocity, σ denotes the standard deviation and $\mathcal{W}(\cdot)$ is an uncorrelated Gaussian process with zero mean with unit variance and is independent. Therefore we define the components of $\boldsymbol{v}_n(\cdot)$, that is, $v_n^x(\tau)$ and $v_n^y(\tau)$ in (9), as follows

$$v_n^x(\tau) = \alpha v_n^x(\tau - 1) + (1 - \alpha)\mu^x + \sigma^x\sqrt{1 - \alpha^2}\mathcal{W}^x(\tau - 1) \tag{11}$$

$$v_n^y(\tau) = \alpha v_n^y(\tau - 1) + (1 - \alpha)\mu^y + \sigma^y\sqrt{1 - \alpha^2}\mathcal{W}^y(\tau - 1) \tag{12}$$

We define the direction of each PHEV n, that is, $\theta_n(\cdot)$, as follows

$$\theta_n(\cdot) = \tan^{-1}\left(\frac{v_n^y(\cdot)}{v_n^x(\cdot)}\right) \tag{13}$$

To design the mobility model, we consider that α is a constant and $0 \leq \alpha \leq 1$.

3.2 Communication model for mobile smart grid environment

We assume that the communication topology between the micro-grids and the PHEVs is a wireless mesh network. We use the IEEE 802.11b protocol for communication between the micro-grids and the PHEVs. Initially, each PHEV $n \in \mathcal{N}^p(\cdot)$ sends a request message having information of the amount of required energy. The request message format of each PHEV is shown in Fig. 2*a*.

On the basing of the total amount of requested energy, each micro-grid decides the price coefficient, $p_m(\cdot)$ and the price per unit energy to be paid by each PHEV. The reply message format of each micro-grid is shown in Fig. 2*b*.

4 Energy trading network topology control game

4.1 Why multi-leader multi-follower stackelberg game?

In an energy trading network, each PHEV tries to charge its battery by consuming high amount of energy. On the other hand, each micro-grid tries to maximise its revenue by deciding an optimum price per unit energy. In the proposed scheme, ENTRANT, we considered that each PHEV can communicate with multiple micro-grids. In such a scenario, the PHEVs initiate the energy trading process by broadcasting the amount of energy to be consumed, and the micro-grids follow the process by replying with the information of price per unit energy. Thereby, we use 'multi-leader multi-follower Stackelberg game' [7], where the PHEVs act as leaders and the micro-grids act as followers.

4.2 Game formulation

To study the interaction between the PHEVs and the micro-grids in ENTRANT, we use a non-cooperative multi-leader multi-follower Stackelberg game theoretic approach [7]. In ENTRANT, each PHEV acts as a leader and needs to decide the amount of energy to be requested to the selected micro-grid. The micro-grids are the followers, which decide the price per unit energy based on the amount of requested energy by the leaders, that is, the PHEVs. The components of the proposed scheme, ENTRANT, are as follows:

(i) Each PHEV $n \in \mathcal{N}^p(\cdot)$ selects a micro-grid $\tilde{m}$ from the set of available micro-grids, that is, $\mathcal{M}$, within the communication range.

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(ii) Each PHEV $n \in \mathcal{N}^p(\cdot)$ decides the amount of energy to be requested, that is, $d_n^p(\cdot)$, to the selected micro-grid $\tilde{m} \in \mathcal{M}$, when each micro-grid m has $\mathcal{E}x_m(\cdot)$ amount of excess energy after meeting the requirement of the set of connected customers, that is, $\mathcal{N}^c(\cdot)$.
(iii) Based on the requested amount of energy by the PHEVs, $\mathcal{N}_m^p(\cdot)$, each micro-grid $m \in \mathcal{M}$ decides the price coefficient $p_m(\cdot)$ using (7).

4.2.1 Utility function of a PHEV: In the proposed scheme, ENTRANT, the utility function of each PHEV $n \in \mathcal{N}^p(\cdot)$, that is, $\mathbb{U}_n^{\tilde{m}}(\cdot)$, represents the satisfaction factor PHEV n by consuming $d_n^p(\cdot)$ amount of energy from micro-grid $\tilde{m}$. The satisfaction factor of each PHEV $n \in \mathcal{N}^p(\cdot)$ is defined in Definition 3.

Definition 3: The satisfaction factor of each PHEV $n \in \mathcal{N}^p(\cdot)$ is evaluated with the ratio of the amount of energy requested to the selected micro-grid $\tilde{m} \in \mathcal{M}$, that is, $d_n^p(\cdot)$ and the maximum amount of energy required, that is, $maxd_n^p(\cdot)$ defined as below

$$\max d_n^p(\cdot) = E_n^{\max} - E_n^{\text{res}}(\cdot) \tag{14}$$

where $E_n^{\max}$ and $E_n^{\text{res}}(\cdot)$ are the maximum battery capacity and the residual energy of each PHEV $n \in \mathcal{N}^p(\cdot)$, respectively.

We define the rules for utility calculation of each PHEV n as follows:

(i) The utility function of each PHEV n, $\mathbb{U}_n^{\tilde{m}}(\cdot)$, is considered to be a non-decreasing function. Hence, in each time-slot, with the increase in the amount of consumed energy $d_n^p(\cdot)$, that is, $\bar{d}_n^p(\cdot) = \tilde{d}_n^p(\cdot) - d_n^p(\cdot)$, the satisfaction factor of each PHEV n becomes higher. Here, $\tilde{d}_n^p(\cdot)$ and $d_n^p(\cdot)$ are the new and the modified recent amount of requested energy by PHEV n to the selected micro-grid $\tilde{m} \in \mathcal{M}$. Mathematically

$$\frac{\delta \mathbb{U}_n^{\tilde{m}}(\cdot)}{\delta \tilde{d}_n^p(\cdot)} \geq 0 \tag{15}$$

(ii) The marginal utility of each PHEV n is considered to be decreasing, as with increase in consumed energy after reaching equilibrium state, the PHEVs will be over powered or the PHEVs have to pay a huge amount. Mathematically

$$\frac{\delta^2 \mathbb{U}_n^{\tilde{m}}(\cdot)}{\delta[\tilde{d}_n^p(\cdot)]^2} < 0 \tag{16}$$

(iii) The amount of energy to be consumed reduces with the increase in price coefficient. Therefore the utility value of $\mathbb{U}_n^{\tilde{m}}(\cdot)$ reduces with the increase in price coefficient of the selected micro-grid $\tilde{m} \in \mathcal{M}$. Mathematically

$$\frac{\delta \mathbb{U}_n^{\tilde{m}}(\cdot)}{\delta p_{\tilde{m}}(\cdot)} < 0 \tag{17}$$

Therefore for each PHEV $n \in \mathcal{N}^p(\cdot)$, we define the revenue function, $\mathbb{R}_n^p(\cdot)$ and the cost function, $\mathbb{C}_n^p(\cdot)$, in Definitions 4 and 5, respectively. We consider that the utility function, $\mathbb{U}_n^{\tilde{m}}(\cdot)$, of each PHEV n is defined as the difference of revenue function, $\mathbb{R}_n^p(\cdot)$ and the cost function, $\mathbb{C}_n^p(\cdot)$. Mathematically

$$\mathbb{U}_n^{\tilde{m}}(\cdot) = \mathbb{R}_n^p(\cdot) - \mathbb{C}_n^p(\cdot) \tag{18}$$

Definition 4: The revenue function of each PHEV n, that is, $\mathbb{R}_n^p(\cdot)$, is considered to be a concave function. Therefore we define the revenue function, $\mathbb{R}_n^p(\cdot)$, as follows

$$\begin{aligned}\mathbb{R}_n^p(\cdot) &= E_n^{\max} \tan^{-1}\left(\mathrm{e}^{-\left(\bar{d}_n^p(\cdot)/\tilde{d}_n^p(\cdot)\right)}\right) \\ &= E_n^{\max} \tan^{-1}\left(\mathrm{e}^{-\left(\tilde{d}_n^p(\cdot) - d_n^p(\cdot)/\tilde{d}_n^p(\cdot)\right)}\right)\end{aligned} \tag{19}$$

Definition 5: The cost function of PHEV $n \in \mathcal{N}^p(\cdot)$, that is, $\mathbb{C}_n^p(\cdot)$, is considered to be a linear function having linear coefficient of the selected micro-grid $\tilde{m}$, that is, price coefficient defined in (7). Mathematically

$$\begin{aligned}\mathbb{C}_n^p(\cdot) &= p_{\tilde{m}}(\cdot)\,\tilde{d}_n^p(\cdot) \\ &= f\left(\frac{\sum_{n=1}^{n\in\mathcal{N}_m^p(\cdot)} e_n^p(\cdot)}{\mathcal{E}x_m(\cdot)}\right) e_n^p(\cdot) \\ &= \frac{\sum_{n=1}^{n\in\mathcal{N}_m^p(\cdot)} e_n^p(\cdot)}{\mathcal{E}x_m(\cdot)} e_n^p(\cdot)\end{aligned} \tag{20}$$

Therefore using Definitions 4 and 5, we redefine the utility function $\mathbb{U}_n^{\tilde{m}}(\cdot)$ as follows

$$\begin{aligned}\mathbb{U}_n^{\tilde{m}}(\cdot) &= E_n^{\max} \tan^{-1}\left(\mathrm{e}^{-\left(\tilde{d}_n^p(\cdot) - d_n^p(\cdot)/\tilde{d}_n^p(\cdot)\right)}\right) \\ &\quad - p_{\tilde{m}}(\cdot)\,\tilde{d}_n^p(\cdot)\end{aligned} \tag{21}$$

4.2.2 Utility function of a micro-grid: In the proposed scheme, ENTRANT, each micro-grid $m \in \mathcal{M}$ makes profit by selling the excess amount of energy to the set of connected PHEVs, that is, $\mathcal{N}^p(\cdot)$. Each micro-grid m calculates the price coefficient, $p_m(\cdot)$, based on the amount of requested energy by the PHEVs $\mathcal{N}_m^p(\cdot)$, that is, $\sum_{n=1}^{n\in\mathcal{N}_m^p(\cdot)} \tilde{d}_n^p(\cdot)$. The utility of each micro-grid $m \in \mathcal{M}$, that is, $\mathbb{B}_m^p(\cdot)$, represents the profit of each micro-grid m by selling the excess amount of energy. Therefore we define the utility function, $\mathbb{B}_m^p(\cdot)$, of each micro-grid $m \in \mathcal{M}$ as follows

$$\mathbb{B}_m^p(\cdot) = \left[p_m(\cdot) - c_m(\cdot)\right] \sum_{n=1}^{n\in\mathcal{N}_m^p(\cdot)} \tilde{d}_n^p(\cdot) \tag{22}$$

where $c_m(\cdot)$ is the generation-cost coefficient of each micro-grid $m \in \mathcal{M}$.

In ENTRANT, each PHEV $n \in \mathcal{N}$ and each micro-grid $m \in \mathcal{M}$ try to maximise the payoff of the utility function, individually, following the proposed non-cooperative game theoretic approach.

4.3 Existence of generalised nash equilibrium solution

We determine the existence of generalised Nash equilibrium solution using variational inequality [34] as shown in Theorem 1.

Theorem 1: Given a fixed amount of energy to be consumed by each PHEV, there exists a generalised Nash equilibrium solution, as there exists a variational inequality solution, for each PHEV n and each micro-grid m. Hence, each PHEV selects micro-grid $\tilde{m}$over micro-grid m and each micro-grid decides the price coefficient, $p_m(\cdot)$, while satisfying the following constraints

$$\mathbb{U}_n^{\tilde{m}}(\cdot) \geq \mathbb{U}_n^m(\cdot), \quad \text{where } \forall m, \quad \tilde{m} \in \mathcal{M} \tag{23}$$

$$\mathbb{B}_m^{p*}(\cdot) \geq \mathbb{B}_m^p(\cdot) \tag{24}$$

where $\mathbb{B}_m^{p*}$ is the utility function of micro-grid m at Nash equilibrium point.

Proof: The utility function of each PHEV n, that is, $\mathbb{U}_n^m(\cdot)$ and the utility function of each micro-grid m, that is, $\mathbb{B}_m^p(\cdot)$, need to be maximised. Hence, applying Karush–Kuhn–Tucker conditions, we obtain

$$\begin{gathered}\nabla_n \mathbb{U}_n^m(\cdot) = \nabla_n \lambda_n(\cdot) \left[\mathcal{E}x_m(\cdot) - \sum_{n=1}^{n \in \mathcal{N}_m^p(\cdot)} \tilde{d}_n^p(\cdot) \right] \\ \nabla_n \lambda_n(\cdot) \left[\mathcal{E}x_m(\cdot) - \sum_{n=1}^{n \in \mathcal{N}_m^p(\cdot)} \tilde{d}_n^p(\cdot) \right] = 0, \quad \text{and} \quad \lambda_n(\cdot) > 0\end{gathered} \tag{25}$$

where $\lambda_n(\cdot)$ is the Lagrangian constant. Considering an overall utility function, we obtain

$$\nabla \mathcal{U}^m(\cdot) - \nabla \boldsymbol{\lambda}(\cdot) \left[\mathcal{E}x_m(\cdot) - \sum_{n=1}^{n \in \mathcal{N}_m^p(\cdot)} \tilde{d}_n^p(\cdot) \right] = 0 \tag{26}$$

where $\mathcal{U}^m(\cdot) = \sum \mathbb{U}_n^m(\cdot)$ and $\boldsymbol{\lambda} \triangleq \lambda_1 \triangleq \cdots \triangleq \lambda_{|\mathcal{N}_m^p(\cdot)|}$. Hence, we obtain the Jacobian matrix of $\mathcal{U}^m(\cdot)$ as follows

$$\boldsymbol{J}\mathcal{U}^m(\cdot) = \begin{bmatrix} K_1 & \cdots & 0 & \cdots & 0 \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ 0 & \cdots & K_n & \cdots & 0 \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ 0 & \cdots & 0 & \cdots & K_{|\mathcal{N}_m^p(\cdot)|} \end{bmatrix} \tag{27}$$

where

$$K_n = \frac{E_n^{\max} e_n^p}{[\tilde{d}_n^p]^2 + [\bar{d}_n^p]^2} \mathrm{e}^{-\left(\bar{d}_n^p/\tilde{d}_n^p\right)} - p_m(\cdot)$$

$\boldsymbol{J}\mathcal{U}^m(\cdot)$ is a positive diagonal matrix, as we assume that the amount of requested energy for each PHEV n is non-negative. Therefore we conclude that there exists variational inequality solution, that is, generalised Nash equilibrium solution. □

4.4 Algorithms

To reach the equilibrium of energy trading networks using the proposed scheme, ENTRANT, the PHEVs and the micro-grids take their respective strategies, while incurring marginal communication overhead. In this paper, we propose two different algorithms — (a) for PHEV and (b) for micro-grid, as shown in Algorithms 1 and 2 (see Figs. 3 and 4), respectively. Each PHEV n decides the amount of energy to be requested to the selected micro-grid using Algorithm 1 (Fig. 3). On the other hand, each micro-grid m calculates the price coefficient based on the amount of energy requested by the connected PHEVs using Algorithm 2 (Fig. 4), and broadcasts the calculated price coefficient, $p_m(\cdot)$.

Algorithm 1

Inputs : E_n^{max}: Maximum battery capacity of PHEV n
$E_n^{res}(\cdot)$: Residual energy of PHEV n
$d_n^p(\cdot)$: Current value of request energy by PHEV n
$p_m(\cdot)$: price co-efficient of each micro-grid $m \in \mathcal{M}$
Outputs: $\tilde{d}_n^p(\cdot)$: Modified value of request energy by PHEV n
$\tilde{m}$: Selected micro-grid for energy supply
Calculate $\tilde{d}_n^p(\cdot)$ using following equation:
$\tilde{d}_n^p(\cdot) = (1 + \frac{E_n^{res}(\cdot)}{E_n^{max}}) d_n^p(\cdot)$
// $\frac{E_n^{res}(\cdot)}{E_n^{max}}$ is allowable change in energy request
Calculate $\mathbb{U}_n^m(\cdot)$, where $\forall m \in \mathcal{M}$
if $\max \mathbb{U}_n^m(\tau) > \mathbb{U}_n^{\tilde{m}}(\tau - 1)$ **then**
  if $\mathbb{U}_n^{\tilde{m}}(\cdot) \geq \mathbb{U}_n^m(\cdot)$ **then**
    Request micro-grid $\tilde{m}$ to supply $\tilde{d}_n^p(\cdot)$ amount of energy
  else
    Request micro-grid m to supply $\tilde{d}_n^p(\cdot)$ amount of energy
  end
else
  $\tilde{d}_n^p(\cdot) = d_n^p(\cdot)$
  // Nash Equilibrium reached
  Request previously selected micro-grid $\tilde{m}$ to supply $\tilde{d}_n^p(\cdot)$ amount of energy
  // Here, $\tilde{m}$ is the selected micro-grid in the previous iteration
end
return

Fig. 3 *ENTRANT algorithm for PHEV*

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Algorithm 2

Inputs : $\tilde{d}_n^p(\cdot)$: Amount of request energy by PHEV n
$c_m(\cdot)$: Generation-cost coefficient of micro-grid m
$\mathcal{E}x_m(\cdot)$: Excess amount of generated energy
Output: $p_m(\cdot)$: Price coefficient of micro-grid m
Calculate $p_m(\cdot)$ using Equation (7)
if $\mathbb{B}_m^p(\tau) == \mathbb{B}_m^p(\tau - 1)$ **then**
  `// Nash Equilibrium reached`
end
Broadcast the price coefficient $p_m(\cdot)$
return

Fig. 4 *ENTRANT algorithm for micro-grid*

5 Performance evaluation

5.1 Simulation parameters

For performance evaluation, we consider randomly generated positions of the micro-grids and the initial positions of the PHEVs on a MATLAB simulation platform, as shown in Table 2. In this work, we assumed that each PHEV follows the Gauss–Markov mobility model. Therefore we calculated the position of the PHEVs using (9), (11) and (12). We considered randomly generated values for maximum battery capacity of the PHEVs.

In a coalition, each residential customer, that is, home-users, decides his/her energy consumption profile *a priori*. Hence, based on the amount of energy generated by the micro-grids using renewable energy resources, each micro-grid calculates the amount of excess energy generated. For the sake of simulation, we considered that each micro-grid has a fixed amount of excess energy, that is, 90 MWh [35] and the residual energy at the PHEV-end is generated randomly. Hence, based on the amount of requested energy by the connected PHEVs, each micro-grid decides the price coefficient and the price to be paid by each customer.

5.2 Benchmark

The performance of the proposed scheme, ENTRANT, is evaluated by comparing the results with other energy trading policies, such as the economics of electric vehicle charging (E2VC) [35], the energy trading without any game-theoretic approach (WoENT).

We refer to these different energy trading policies as ENTRANT, E2VC and WoENT, through the rest of the paper. In E2VC [35], the authors proposed a non-cooperative game theoretic approach. Although the authors did not consider the choice of multiple micro-grids for each PHEV available in the coalition. In WoENT, we considered that each PHEV chooses the appropriate micro-grid from the available micro-grids based on the minimum distance to be traveled. Thus, we can improve the satisfaction factor of the PHEVs, and the energy load to each micro-grid using the proposed scheme, ENTRANT, than using other approaches, that is, E2VC and WoENT.

5.3 Performance metrics

(i) *Consumed energy per iteration:* The utilisation of excess amount of energy generated can be visualised with the amount of consumed energy per iteration. In each iteration, with the increase in consumed energy by the PHEVs, the satisfaction factor of the micro-grids increases, as higher amount of energy is consumed by the PHEVs.

(ii) *Energy price per micro-grid:* Each PHEV wants to consume energy with lower price. However, if the energy-load to any micro-grid becomes higher, the price per unit energy of that micro-grid becomes high, while using dynamic pricing strategy. Hence, to utilise the excess amount of generated energy of each micro-grid, we need to distribute the energy request such that the price per unit energy becomes moderated, that is, neither too high nor too low.

(iii) *Price paid per PHEV:* Based on the price per unit energy decided by the micro-grids and amount of energy to

Table 1 List of symbols

Symbol	Description
$\mathcal{M}$	set of micro-grids in a coalition
$\mathcal{N}(\cdot)$	set of consumers in a coalition
$\mathcal{N}^c(\cdot)$	set of customers in a coalition
$\mathcal{N}^p(\cdot)$	set of PHEVs in a coalition
$\mathcal{T}$	set of time slots in a day
$d_n(\cdot)$	amount of energy requested by consumer n
$d_n^c(\cdot)$	amount of energy requested by customer n
$d_n^p(\cdot)$	amount of energy requested by PHEV n
$\tilde{d}_n^p(\cdot)$	new amount of energy requested by PHEV n
$\mathbb{U}_n^m(\cdot)$	utility function of PHEV n connected with micro-grid m
$\mathbb{R}_n^p(\cdot)$	revenue function of PHEV n
$\mathbb{C}_n^p(\cdot)$	cost function of PHEV n
$\mathcal{G}_m(\cdot)$	amount of energy generated by micro-grid m
$\mathcal{C}_m(\cdot)$	amount of energy consumed by customers from micro-grid m
$\mathcal{E}x_m(\cdot)$	amount of excess energy generated by micro-grid m
$\mathcal{E}x_m^{res}(\cdot)$	remaining amount of excess energy generated by micro-grid m
$p_m(\cdot)$	price per unit energy decided by micro-grid m
$s_m(\cdot)$	satisfaction factor of micro-grid m
$\mathbb{B}_m^p(\cdot)$	utility function of micro-grid m
$\mathbb{B}_m^{p*}(\cdot)$	utility function of micro-grid m at Nash equilibrium

Table 2 Simulation parameters

Parameter	Value
simulation area	20 km × 20 km
number of micro-grids	4
number of PHEVs	500
maximum battery capacity	35–65 MWh
residual energy of each PHEV	>10 MWh
excess energy per micro-grid	99 MWh

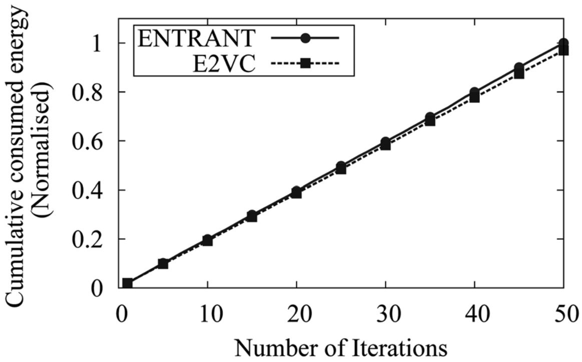

Fig. 5 *Consumed energy per iteration*

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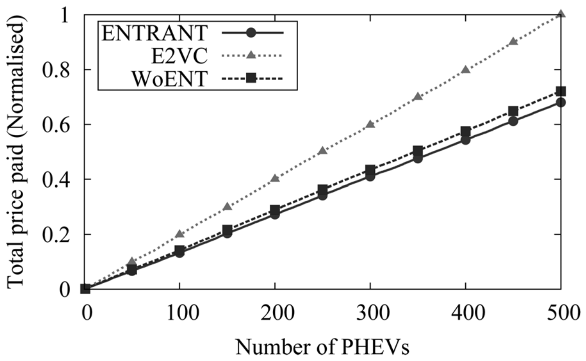

Fig. 6 *Price paid by the PHEVs*

consumed by each PHEV, each micro-grid decides the amount of billing for each PHEV. However, the price decided by the micro-grids and the amount of energy requested by each PHEV are interdependent. If the amount of energy requested by each micro-grid becomes too high, the price becomes high. As a result, each PHEV needs to re-decide the amount of energy to consumed and request the selected micro-grid. On the other hand, if the price per unit energy decided by the micro-grid becomes too low, each PHEV requests high amount of energy. Therefore the price per unit energy becomes high.

(iv) *Satisfaction factor of PHEVs:* Satisfaction factor of each PHEV is defined as the ratio of the amount of energy consumed, and the total demand of a PHEV. Hence, higher satisfaction factor signifies higher portion of required energy is served by the micro-grid. Each PHEV behaving rationally tries to maximise its satisfaction factor by consuming higher amount of energy.

(v) *Quality of energy service:* We consider that higher utility value signifies higher QoS. Therefore each PHEV tries to obtain higher QoS by maximising the payoff of the its utility function.

5.4 Results and discussions

For simulation purpose, we assume that each micro-grid calculates the real-time supply and demand in every 10 s interval. Each micro-grid has 99 MWh excess amount of energy that can be sold to the available PHEVs within the coalition. Hence, each micro-grid makes profit by selling the excess amount of energy. On the other hand, the maximum energy storage capacity of the PHEVs are chosen randomly from a range of 35–65 MWh. The residual energy of the PHEVs are also selected randomly in between 10

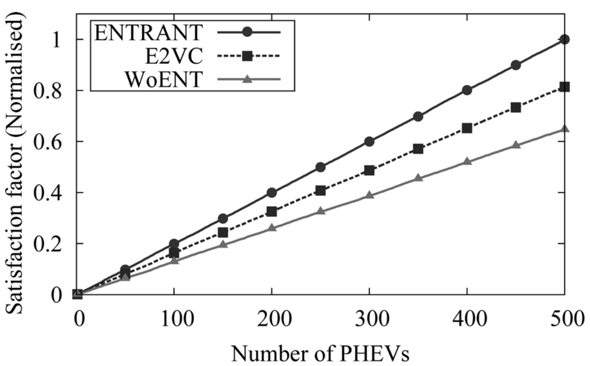

Fig. 7 *Satisfaction factor of the PHEVs*

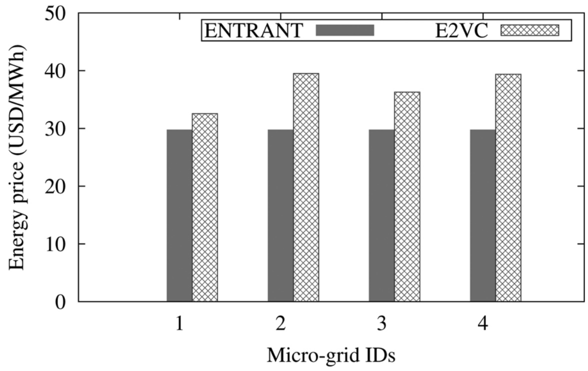

Fig. 8 *Energy price per micro-grid*

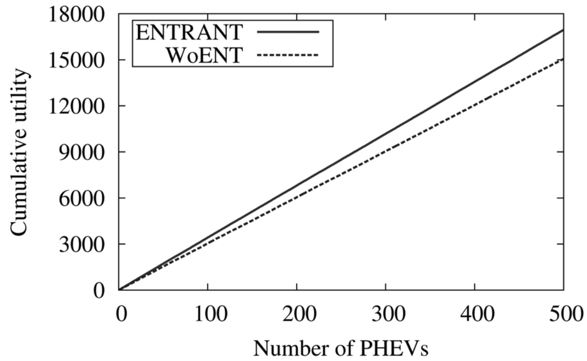

Fig. 9 *Utility value of the PHEVs*

MWh and the maximum storage capacity of each PHEV, individually. Here, we consider that each PHEV is the collection of 100 electric vehicles (EVs). We took 500 PHEVs, and 4 micro-grids for simulation purpose.

Fig. 5 shows that the cumulative energy consumed per iteration is higher using the proposed scheme, ENTRANT, than using E2VC. Therefore we conclude that within a coalition, each PHEV consumes higher amount of energy using ENTRANT, than using E2VC. Therefore utilisation of generated energy is much higher using ENTRANT, than using E2VC.

In Fig. 6, the variation of the price paid by the PHEVs within a coalition is shown. Using ENTRANT, the PHEVs have to pay less, as the energy is properly distributed within the available micro-grids within a coalition. Hence, we conclude that in a coalition, the PHEVs obtain s the required energy by paying less while using the proposed scheme, ENTRANT, than using E2VC and WoENT.

Fig. 7 shows that the cumulative satisfaction factor is much higher using ENTRANT, than using E2VC. Therefore we conclude that using the proposed scheme, ENTRANT, each PHEV consumes higher percentage of energy of its requirement to charge its battery fully.

Although the total price paid by the PHEVs is almost similar using the approaches ENTRANT and WoENT, as shown in Fig. 6, the amount of consumed energy by the PHEVs, that is, the satisfaction factor of the PHEVs, is higher using ENTRANT, than using WoENT, as shown in Fig. 7. Therefore we conclude that using the proposed scheme, ENTRANT, the PHEVs consume higher amount of energy while paying less, than using E2VC and WoENT.

Fig. 8 shows that the price per unit energy, that is, USD/MWh, is lower using ENTRANT, than using E2VC. Using ENTRANT, the price per unit energy is almost similar for

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each micro-grid, as the energy load is properly distributed within the available micro-grids within a coalition.

Fig. 9 shows that the payoff, that is, utility, of the utility function of each PHEV is much higher using ENTRANT, than using WoENT. Hence, we conclude that each PHEV can obtain higher QoS using ENTRANT, than using WoENT.

6 Conclusions

In this paper, we formulated a multi-leader multi-follower Stackelberg game theoretic approach to study the problem of ENTRANT. Based on the proposed approach, that is, ENTRANT, we showed how energy can be distributed within the PHEVs within a coalition having multiple micro-grids. The simulation results show that the proposed scheme, ENTRANT, yields improved results.

Future extension of this work includes understanding how the energy trading network topology can be controlled in advance based on the estimated trajectory of the PHEVs, so that scheduling in energy trading has less delay and the energy can be properly distributed within a single coalition, that is, multiple micro-grids, or multiple coalitions.

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