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Energy management of Plug-In Hybrid Electric Vehicles in renewable-based energy hubs

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ABSTRACT

Proliferation of Plug-in Hybrid Electric Vehicles (PHEVs) and integration of various distributed generation (DG) technologies have been recognized to play an undeniable role in modern power systems of the future. In order to effectively model the interactions of these two technologies, this paper develops a multi-criteria framework to coordinate the charging behaviors of PHEVs within an energy hub platform. In this regard, the desirable charging profiles from the viewpoint of both PHEV owners and hub manager are first captured and reported to the PHEVs Coordinator Entity (PCE). The PCE, then, runs an optimization framework in which several criteria including the PHEV owners' convenience, energy hub's profit, and the technical performance of the distribution grid are all taken into account as a multi-criteria optimization framework resulting in the PHEVs' optimal charging patterns. The proposed strategy is applied to the modified IEEE 34-node test system and the results demonstrate the applicability and efficiency of the proposed framework.

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1. Introduction

DEPLETING fossil fuel reserves and growing awareness on the global warming and pollution concerns have led to expeditiously rising energy prices and major issues around the future energy security [1–3]. In most countries, transportation sector is a major consumer of fossil fuels that aggravates the "oil addiction" problem and is a key driver for development of new technologies [4]. Emergence of new vehicles in the form of either Plug-in Hybrid Electric Vehicles (PHEVs) or Electric Vehicles (EVs) has established a new policy in transportation sector to replace relatively inefficient vehicles with Internal Combustion Engines (ICEs) by electric alternatives. This policy shifts the energy demand for transportation targets from crude oil to electricity that result in less environmental pollution [5].

However, high penetration of PHEVs, if not properly managed, may introduce significant negative impacts on the operation of power systems. Reviews in [6,7] indicate that uncontrolled charging of PHEVs, so-called "*dumb charging*" [8], will impose new peak loads to power distribution systems. Once these new peaks coincide with the maximum demand of other electrical loads in the system, it can provoke voltage excursions, equipment overloads, energy losses, and the need for network reinforcement [9]. Benefiting from the price signals and various time-based tariffs, e.g., time-of-use (ToU) schemes, can be regarded as the first response to PHEVs uptake [10]. Even though tariffs can transfer the electrical charging demand from peak to off-peak periods, multiple-tariff charging schemes alone cannot efficiently solve the PHEVs charging challenges [11]. The need, therefore, arises for an efficient charging control framework being able to coordinate charging behavior of various vehicles such that no new peak load would be created by PHEVs charging demand.

In this respect, several management algorithms for PHEVs charging demand have been introduced in the literature [12–17], most of which adopt either decentralized/distributed control [12–14] or centralized control [15–17]. In the latter, the system operator would decide about the time and rate of the PHEVs charging. This charging control policy has been shown to work efficiently from the viewpoint of power distribution companies [17,18]. In the decentralized approaches, the customers themselves can determine the desired charging profiles of their vehicles. This charging control policy, therefore, can efficiently represent the main concerns of EV owners. Each of these two charging policies has its advantages and disadvantages. These approaches would bring about various challenges; the decentralized policies, though supporting autonomy and privacy of customers, fails in reaching optimal charging profiles for large PHEVs fleet especially when taking into account the system technical concerns. On the other hand, the centralized frameworks are inefficient for customers who commonly identify their energy consumption patterns themselves.

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Nomenclature

A. Constants and Parameters

CHP_{Cap}	Electrical capacity of the combined heat and power unit (CHP)
$CPen$	Penalty cost of one kWh energy deviation
$CRw_{(.)}$	The reward of one kWh energy deviation
$E_{(.)}^{Rq.}$	Required energy for charging of PHEVs
Fur_{Cap}	Furnace capacity
$l_{(.),(.)}$	Non-PEHV electrical load at a node
$L_e^{non-PHEV}(.)$	Non-PHEV electrical load
$L_h(.)$	Heat load of the energy hub
$L_e(.)$	Electricity load of the energy hub
$PC_{(.)}^{max}$	Maximum charging level of the PHEVs
$Pr_e(.)$, $Pr_g(.)$	Electricity and natural gas price at input layer of the energy hub
$t_s^{(.)}$, $t_f^{(.)}$	Plugging and departure time of the PHEV
$T_e(.)$, $T_h(.)$	Heat and electricity tariffs
$UTF_{(.),(.)}$	Unwillingness of the PHEVs
η_{CHP}^e, η_{CHP}^{Th}, η_{Conv}, η_{Fur}, η_{Trans}	CHP-electrical, CHP-thermal, converter, furnace, and transformer efficiencies
μ_{Load}	The system load average
ΔT	Time interval

B. Variables and Functions

$Cost(.)$, $Rev(.)$	Cost and revenue of the energy hub
$Dev(.)$	Total deviation of PHEV charging schedule
Hub_{share}^l	Share of energy hub in TRC for scenario l
$L_e^{PHEV}(.)$	PHEVs charging demand
$P_e(.)$, $P_g(.)$, $P_w(.)$	Electrical energy, natural gas, and wind turbine output received at input ports of the energy hub
$pc_{(.),(.)}$	Charging level of PHEVs
$\boldsymbol{PC}_{(.)}^{Des.}$	Desired charging schedule of PHEVs
$\boldsymbol{PC}_{(.)}^{Opt.}$	Optimal charging schedule of PHEVs attained by the proposed procedure
$\boldsymbol{PC}_{(.)}^{Prof}$	Optimal charging profile of PHEV from the viewpoint of the energy hub operator
$Pen_{(.)}$	Penalty cost of the PHEV
$Prof_{(.)}$	Energy hub's earned profit
$Rw_{(.),(.)}$	Total reward of PHEV
$s_{b,(.)}$	Electrical load at node b
Ten_{Hub}^l	Tendency of the energy hub for scenario l
$v(.)$	Dispatch factor of the energy hub

C. Sets

B	Set of distribution network buses
T	Set of time intervals in a day
V	Set of PHEVs in distribution network
V_h	Set of PHEVs connected to the house outlet

For instance, the authors in [19] proposed an energy management framework for PHEVs charging management considering varying oil and electricity prices. In [20], a charging scheme is presented for PHEVs within a microgrid that aims to minimize the imported power from the upstream grid and maximizes the deployment of renewable generations within the microgrid. Although both frameworks can effectively handle the main requirements of the system operator in different operating conditions, they are unable to address the EV owners' convenience. These charging control strategies also cannot motivate the EV owners to adopt the charging schedule programs. On the other hand, authors in [21,22] have adopted distributed/decentralized schemes for cooperative energy management of PHEVs, that although they respect PHEVs owner privacy, fail in reaching optimal charging profiles for large PHEVs fleets, especially when considering the system technical concerns.

2. Original contributions

As discussed in the previous section, the above-introduced efforts have been unable to satisfy the main requirements of all the players, while in the meantime capturing the future visions of the energy networks. In response, this paper proposes a holistic PHEV charging management framework to be implemented on a renewable-based energy hub. An energy hub is, in fact, an interface between the distributed generators (DG), customers, and transportation infrastructure [23,24]. Employing this new concept, the system operators can more efficiently deal with various forms of energy transmission, conversion, storage, and consumption [25]. In addition, this concept opens new gateways to capture the synergies of the interdependent network infrastructures [26]. Fig. 1 delineates the main players of the charging control problem. The EV owners play a vital role in prosperity of a charging control strategy. Hence, at the first step of the proposed strategy, EV owners determine the desirable charging patterns of their vehicles via a user-based charging schedule. The attained desirable charging patterns are then reported to a public agent, i.e., PHEVs Coordinator Entity (PCE). This autonomous agent (PCE) is established to reach the charging patterns which are optimal and efficient from the viewpoint of all the players. On the other hand, a renewable-based energy hub, as a private entity, tries to set the charging schedules of PHEVs so as to maximize its profit. In this regard, the energy hub operator runs an optimization problem to find the optimal charging patterns of PHEVs. In order to manage the PHEVs charging demand with EV owners and hub operator requirements and system technical requisites, a multi-criteria optimization is adopted by the PCE. In this optimization framework, load variance of the feeder, customers' convenience criterion, and energy hub profit satisfaction degree have been all taken into account as the optimization criteria.

The remainder of this paper is structured as follows: Section 3 introduces the general structure of the proposed charging control strategy. The PCE multi-criteria charging optimization problem and the proposed solution algorithm are represented in Section 4. The developed PHEVs charging control framework is applied to the modified IEEE 34-node test system, and the applicability and efficiency of the proposed strategy is verified in Section 5. Finally, concluding remarks are presented in Section 6.

3. Architecture of the proposed model

This section is devoted to tasks and roles of the main players associated with the proposed framework.

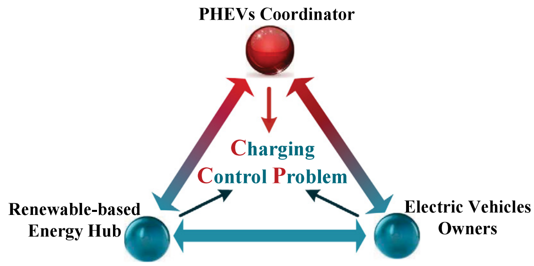

Fig. 1. Main players of the proposed charging control strategy.

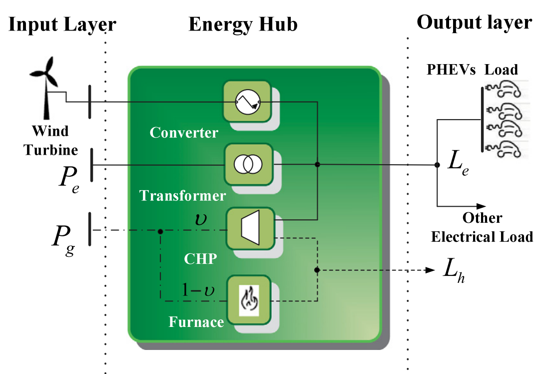

Fig. 2. Architecture of the proposed renewable-based energy hub.

3.1. Renewable-based energy hub

Energy hub offers an opportunity to benefit from a number of prospective advantages over conventional decoupled sources of energy supply, e.g., higher flexibility and reliability in the load supply and energy demand [27,28]. In order to have a realistic view of the EVs impacts on the future power systems, charging management of EVs should be analyzed in the context of energy hubs. To successfully model the interactions of these two technologies, the proposed charging control strategy is implemented on a renewable-based energy hub. General structure of the proposed energy hub is shown in Fig. 2.

Reducing the emission produced by transportation sector is the main motivation in the wide deployment of PHEVs. This, however, has been neglected in majority of research on PHEVs in the literature. Accordingly, wind turbine has been taken into account to serve the electrical loads. Eq. (1) provides the mathematical description of the energy hub.

$$\begin{cases} L_e^{net}(t) = \eta_{Trans} P_e(t) + \upsilon(t)\eta_{CHP}^{e} P_g(t) \\ L_h(t) = \upsilon(t)\eta_{CHP}^{Th} P_g(t) + (1-\upsilon(t))\eta_{Fur} P_g(t) \end{cases} \tag{1a}$$

$$L_e^{net}(t) = L_e(t) - \eta_{Conv.} P_w(t) \tag{1b}$$

$$L_e(t) = L_e^{PHEV}(t) + L_e^{non-PHEV}(t) \tag{1c}$$

$$L_e^{PHEV}(t) = \sum_{k=1}^{V} pc_{k,t} \tag{1d}$$

Majority of the existing DG investments are commonly made by private investors [29]. Accordingly, it seems more practical to model the proposed energy hub as a financial asset owned by a private investor. In this context, at each time, the energy hub operator should decide on how the input energies to the hub should be dispatched to economically meet the energy loads.

Among the energy loads of the hub, the charging demand of PHEVs ($L_e^{PHEV}(t)$) is controllable and the hub operator would like to determine the charging profiles of PHEVs ($\boldsymbol{PC}_k^{Prof}$) so as to maximize its profit. To achieve this goal, the hub operator runs the following optimization problem,

$$\max \; Prof(t) \tag{2a}$$

$$Prof(t) = \underbrace{T_e(t) \times L_e(t) + T_h(t) \times L_h(t)}_{Rev(t)} - \underbrace{Pr_e(t) \times P_e(t) + Pr_g(t) \times P_g(t)}_{Cost(t)} \tag{2b}$$

As can be inferred from this formula, the energy hub tries to maximize its profit which is constituted of the revenue attained by selling energy to its downstream customers and the costs of purchasing energy from the upstream grid.

The optimization constraints are the energy hub and PHEVs limits which are presented in (3a)–(3e).

$$0 \le \upsilon(t) \le 1 \tag{3a}$$

$$\upsilon(t)\eta_{CHP}^{e} P_g(t) \le CHP_{Cap} \tag{3b}$$

$$(1-\upsilon(t))\eta_{Fur.} P_g(t) \le Fur_{Cap} \tag{3c}$$

$$\sum_{t=t_s^k}^{t_f^k - 1} pc_{k,t} \times \Delta t = E_k^{Rq.} \quad \forall k \in V \tag{3d}$$

$$0 \le pc_{k,t} \le PC_k^{\max} \qquad \forall k \in V,\; t \in [t_s^k,\, t_f^k) \tag{3e}$$

In this set of equations, the first constraint is imposed on the dispatch factor of the energy hub, while the next two constraints satisfy the maximum power limits of the energy hub's CHP, and boiler, respectively. The next constraint guarantees that the desired energy demand of each PHEV is satisfied within the charging domain. Finally, the last constraint limits the charging power of each PHEV to be within its allowable interval. The solution to this optimization problem has been discussed in details in the authors' previous works [30]. With this optimization problem implemented, the hub operator achieves the optimal dispatch of the input carriers and optimal charging profile of the PHEVs. However, there is no guarantee that these profiles can meet the technical requirements of the network operator as well as the vehicle owners' preferences.

3.2. PHEV owners' requirements

The main purpose of a PHEV is to fulfill the driving requirements of its owner. The EV owners' expectations of a charging control strategy are as follows:

- Imposing minimum cost for the PHEV charging.
- Satisfying several constraints such as charging EV within a predetermined time period and supplying the required energy for a fully charged battery.

Incorporating these concerns in the design procedure of a charging control strategy seems a difficult task. In response, as demonstrated in Fig. 3, user-based charging schedule in the first layer of the proposed strategy is deemed to be an effective solution to this problem. Employing this user-based charging schedule provides the vehicle owners an opportunity to directly address all their requirements with no restrictions. In this regard, the PHEV scheduler at each home runs a linear optimization problem with the objective of minimizing the charging cost taking into account both the owner requirements and electricity price signal. Here, ToU pricing scheme is considered as the electricity price signal.

If $\left\{\boldsymbol{PC}_k^{Des.} = \left[pc_{k,t_s^k}, \ldots, pc_{k,t_s^k+i}, \ldots, pc_{k,t_f^k-1}\right] \forall k \in V_h\right\}$ represents the desired charging schedule of the k^{th} PHEV, the scheduler determines $\boldsymbol{PC}_k^{Des.}$ through the following problem.

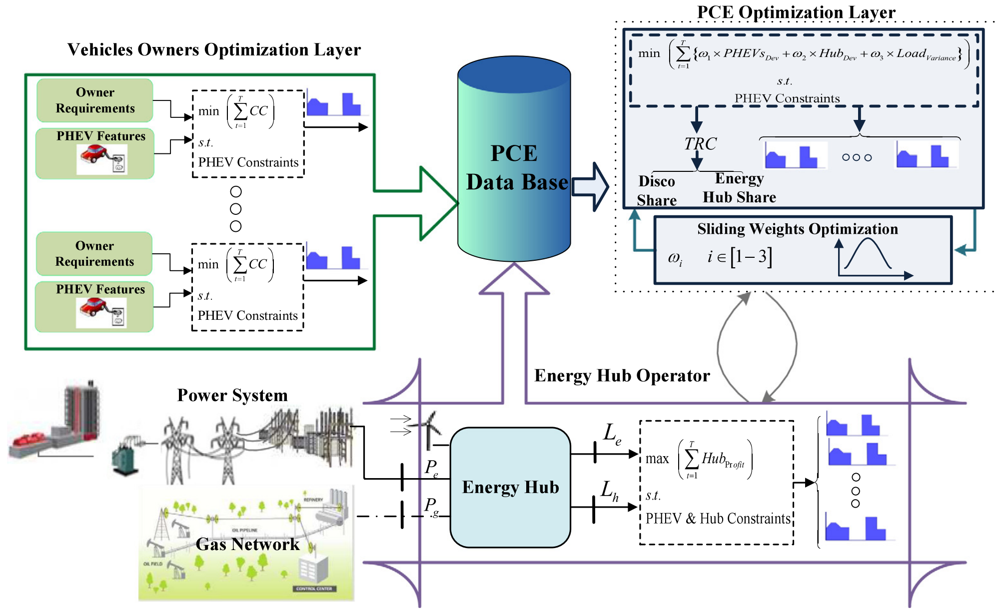

Fig. 3. Main structure of the proposed PHEVs charging control strategy.

$$\min\left(\sum_{v=1}^{V_h}\sum_{t=1}^{T} T_e(t)\times pc_{k,t}\times \Delta t\right) \tag{4a}$$

$s.t.$

$$\sum_{t=t_s^k}^{t_f^k-1} pc_{k,t}\times \Delta t = E_k^{Rq.} \qquad \forall k\in V_h \tag{4b}$$

$$0\le pc_{k,t}\le PC_k^{\max} \qquad \forall k\in V_h, t\in[t_s^k, t_f^k) \tag{4c}$$

In which the objective function is the cost of purchasing the required electricity for charging the PHEVs of each individual house according to electricity tariffs. Besides, the first constraint of this problem guarantees that the required energy demand of each PHEV is satisfied within the allowable charging interval, while the second constraint addresses the charging power limits of each PHEV. Solving this optimization problem, the value of $\boldsymbol{PC}_k^{Des.}$, which is the desired charging schedule of each PHEV, from the viewpoint of PHEVs owners would be identified. A third player, i.e., the PCE, is proposed as an autonomous entity to properly model all these factors in an optimization framework.

3.3. Main tasks of the PCE

At each time, $\boldsymbol{PC}_k^{Des.}$ and $\boldsymbol{PC}_k^{Prof}$ should be reported to the PCE. Neglecting the technical performance requirements of the grid, it can be shown that new peak loads would be consequential employing either $\boldsymbol{PC}_k^{Des.}$ or $\boldsymbol{PC}_k^{Prof}$. In response, the PCE is established to converge the goals and requirements of different players and is tasked with the following:

- Receiving PHEVs data including the allowable charging period and required energy.
- Designing an optimization framework in which the main concerns of all the players are properly modeled.
- Developing a framework to motivate PHEV owners for participation in charging control programs offered by PCE.
- Applying a fair and practical mechanism to establish a link between the hub profit and the imposed costs for PHEVs rescheduling.

By doing so, the PCE considers simultaneously the PHEVs' owners' desires, the energy hub owner's desires, and also the technical constraints of the network. These tasks can be fulfilled by developing a multi-criteria charging framework which is addressed by a multi-objective optimization framework. In this regard, how these tasks are done by this framework and its procedure will be discussed in detail in the next section.

4. PHEVs coordinator modeling outlines

In this section, the main features of the PCE charging optimization framework are delineated.

4.1. The multi-criteria charging framework

As can be traced in Fig. 3, the PCE runs a multi-criteria optimization framework with the following criteria to find the final schedule of PHEVs charging, i.e., $\boldsymbol{PC}_k^{Opt.}$.

4.1.1. PHEV owners' convenience criterion

A key factor in prosperity of any PHEV charging control strategy is the vehicle owners' tendency to participate in such programs. Foundation of control strategies with no attention to customers' requirements would put their practicality under question. As can be seen in Fig. 3, the considered user-based control let the PHEVs owners freely decide about charging strategy of their vehicles. Furthermore, the vehicle owners show different tendencies to participate in corrective programs of the PCE. The PCE, therefore, needs to offer some incentive programs aimed to differentiate between the owners who are willing to participate in these programs and the ones who prefer to adhere to their own plans. To reach a holistic incentive mechanism, three different options are offered by the PCE to the vehicle owners.

• **Prog A**: In this program, customers have no tendency to participate in PCE programs. Hence, PCE should pay penalty for any possible deviations (Dev_k), that is,

$$Dev_k = \sum_{t=1}^{T}(|pc_{k,t}^{Opt.} - pc_{k,t}^{Des.}|\times \Delta t) \quad \forall k\in V \tag{5a}$$

$$Pen_k = Dev_k \times CPen \quad \forall k \in \textbf{Prog A} \tag{5b}$$

• **Prog B:** In this program, customers accept PCE's rescheduling programs with a guarantee of providing the full required charging energy. Based on the value of Dev_k, PCE pays the customers a reward, that is,

$$Rw_{k,B} = Dev_k \times CRw_B \quad \forall k \in \textbf{Prog B} \tag{6}$$

• **Prog C:** The customers who participate in this program have less priority for a fully charged battery. The PCE for these customers assures the charging availability of at least 90% of the vehicle battery capacity. As an incentive for this program, the customers are rewarded as follows:

$$Rw_{k,C} = Dev_k \times CRw_C \quad \forall k \in \textbf{Prog C} \tag{7}$$

It should be noted that $CRw_C > CRw_B$.

Once the incentive policy is defined by the PCE, it needs to incorporate the effects of these programs into its optimization framework. In so doing, the criterion shown in (8) is defined and incorporated in the objective function.

$$\min f_1 = \sum_{k=1}^{V} \sum_{t=1}^{T} UTF_{k,t} \times (pc_{k,t}^{Opt.} - pc_{k,t}^{Des.})^2 \tag{8}$$

Eq. (8) reflects the difference between the optimal PHEV charging profiles and the desired charging weighted by the PHEVs' unwillingness. The parameter $UTF_{k,t}$ gives the EV owners an opportunity to freely determine the unpleasant time intervals for charging. Consequently, if the PHEV owner decides that time interval t is unpleasant for charging, he/she should choose higher values for the $UTF_{k,t}$. Otherwise, this parameter should be set equal to one.

4.1.2. Profit factor of renewable-based energy hub

The hub operator tries to maximize its profit via optimizing the PHEV charging patterns. The $\boldsymbol{PC}_k^{Prof}$ as an appropriate signal reflects the main requirements of the hub operator. To properly consider this signal in the PCE's optimization framework, the following criterion is defined.

$$\min f_2 = \sum_{k=1}^{V} \sum_{t=1}^{T} (pc_{k,t}^{Opt.} - pc_{k,t}^{Prof})^2 \tag{9}$$

4.1.3. Technical performance of the distribution system

With the rise in the number of EVs, power distribution grid could be drastically impacted. As a result, the PCE is forced to introduce a technical criterion to its optimization procedure. To properly model the technical concerns of PHEVs charging demand and reach a convex optimization problem, minimizing the load variance is proposed as the other criterion in the objective function in the PCE's optimization problem [31].

$$\min f_3 = \sum_{t=1}^{T} \frac{1}{T} \left(\sum_{b=1}^{B} (s_{b,t} - \mu_{Load}) \right)^2 \tag{10a}$$

$$s_{b,t} = l_{b,t} + pc_{b,t}^{Opt.} \quad \forall b \in B \tag{10b}$$

$$pc_{b,t}^{Opt.} = \sum_{k \in k_B} pc_{k,t}^{Opt.} \quad \forall b \in B \tag{10c}$$

The weighted sums of these three criteria reflects the PCE's objective function in the charging optimization problem.

$$f = \omega_1 f_1 + \omega_2 f_2 + \omega_3 f_3 \tag{11a}$$

$$\sum_{j=1}^{3} \omega_j = 1 \tag{11b}$$

Finally, the mathematical formulation of the optimization problem can be drawn as follows,

$$\min \; obj = f \tag{12a}$$

$s.t.$

$$\sum_{t=1}^{t_f^k - 1} pc_{k,t} \times \Delta T = E_k^{Rq.} \quad \forall k \notin \textbf{Prog C} \tag{12b}$$

$$0.9E_k^{Rq.} \leq \sum_{t=1}^{t_f^k - 1} pc_{k,t} \times \Delta T \leq E_k^{Rq.} \quad \forall k \in \textbf{Prog C} \tag{12c}$$

$$0 \leq pc_{k,t} \leq PC_k^{\max} \quad \forall k \in V,\ t \in [t_s^k, t_f^k) \tag{12d}$$

4.2. Sliding weights optimization procedure

To solve the quadratic optimization problem shown in (12), the PCE needs to set the values of ω_j. These parameters determine the share of each criterion in the objective function. In addition, implementing any reschedule program calls for a payment mechanism for the customers, while PCE has to supply the required budget for the Total Rescheduling Cost (TRC), that is,

$$TRC = \sum_{k \in \textbf{Prog A}} Pen_k + \sum_{k \in \textbf{Prog B}} Rw_{k,B} + \sum_{k \in \textbf{Prog C}} Rw_{k,C} \tag{13}$$

In this regard, this paper proposes an innovative procedure to optimally set the values of these importance factors and the respective shares of the hub operator and the PCE in supplying the required TRC. This procedure is established based on the concept of *players' tendency*. The step-by-step procedure of this method is illustrated in Fig. 4. Composed of two main blocks, it, in the first block, employs an iterative procedure to set the importance factor for the technical criterion, i.e., ω_3. In this iterative procedure, a tiny value is first chosen for ω_3, i.e., ω_0. Once the values of the other weights are set, the optimization problem addressed in (12) provides the total network losses and compares it with its satisfactory value ($P_{Loss}^{Sat.}$). If this condition is satisfied, the optimal value of ω_3 is reported ($\omega_3^{Opt.}$). Otherwise, the value of ω_3 should be updated as shown in Fig. 4 and this process would be repeated until the satisfactory value for the network losses is attained.

In the second block, another iterative procedure is proposed to optimally set the value of ω_2. At the first iteration, the PCE chooses two different values for ω_2, i.e., a tiny value as ω_{2L}^0 (ω_0'') and a large value as ω_{2H}^0 (ω_0'). Based on these two scenarios, the values of ω_{1L}^0 and ω_{1H}^0 would be calculated as presented in Fig. 4. The optimization problem (12) is run for both scenarios, and the charging schedules ($\boldsymbol{PC}_{Low}^l$ and $\boldsymbol{PC}_{High}^l$) are drawn and reported to the hub operator.

Besides, PCE calculates the required budget for rescheduling programs in each of these two scenarios (TRC_{Low}^l and TRC_{High}^l). The PCE, then, requests to determine its share in supplying TRC (Hub_{Share}^l) to reach the target value of $\boldsymbol{PC}_{High}^l$ rather than $\boldsymbol{PC}_{Low}^l$ by the PCE.

Accordingly, the hub operator runs the optimization problem in (2) taking into account these two charging patterns ($\boldsymbol{PC}_{Low}^l$ and $\boldsymbol{PC}_{High}^l$) as two possible scenarios for L_e^{PHEV}. Consequently, it can find the profit that the hub would earn implementing either $\boldsymbol{PC}_{Low}^l$ ($Prof_{Low}^l$) or $\boldsymbol{PC}_{High}^l$ ($Prof_{High}^l$) as the final charging schedules for the PHEVs. Finally, the hub operator evaluates the Hub_{Share}^l as shown in (14).

$$Hub_{Share}^l = \frac{Prof_{High}^l - Prof_{Low}^l}{2} \tag{14}$$

Once the hub operator decides about its share in TRC of the rescheduling programs and reports to the PCE, the PCE calculates

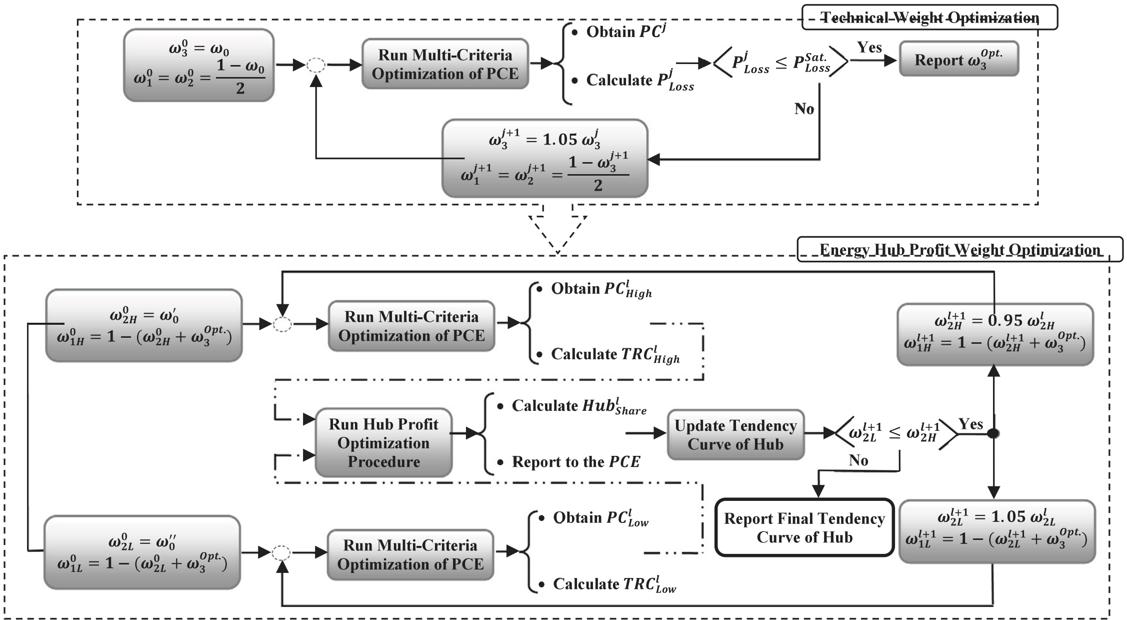

Fig. 4. Structure of sliding weights determination procedure.

the energy hub tendency in providing the required budget for the rescheduling programs in this iteration, which is defined in (15). Then, the PCE updates the ω_{2L}^{l+1} and ω_{2H}^{l+1} values using the formulations presented in Fig. 4.

While the condition ($\omega_{2L}^{l+1} \leq \omega_{2H}^{l+1}$) is satisfied, this process should be repeated so as to extract the next points in the energy hub tendency curve. Finally, the PCE selects the optimal value of the hub importance factor ($\omega_2^{Opt.}$) which is the one that maximizes the energy hub tendency.

$$Ten^l_{Hub} = \frac{Hub^l_{Share}}{TRC^l_{High}} \tag{15}$$

5. Case study and numerical results

In this Section, the proposed charging control strategy is implemented on a modified test system. In this regard, different cases, as tabulated in Table 1, are introduced to investigate the main features of the proposed strategy. In this regard, Case I refers to the reference system with no PHEVs. On the other hand, Cases II to V, respectively, refer to a distribution system in which the PHEVs begin charging as soon as they return homes from their last trip, a system with a user-based charging strategy according to the method explained in Section 2, a system adopting the proposed multi-criteria charging framework, and finally a system in which the PHEVs' charging profiles are determined through the optimization procedure addressed in (2).

5.1. Test system and main assumptions

The modified IEEE 34-node test feeder is selected as a residential distribution system, the single line diagram of which is depicted in Fig. 5 with all data available in [32]. A three-level ToU tariff borrowed from [33] is utilized as electricity tariffs of the energy hub at the output layer ($T_e(t)$). The information about the studied energy hub can be found in [30]. The PJM market electricity prices on 22 July 2013 taken from [34] are used to model the variations of $Pr_e(t)$ at the input layer of the hub. Natural gas prices used in this study are available in [35].

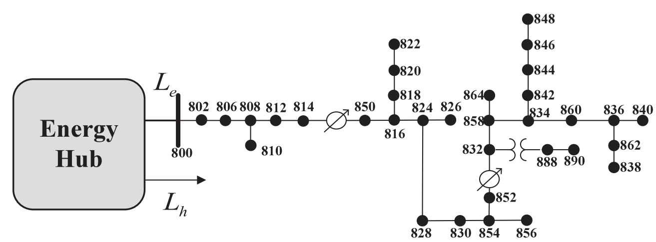

Fig. 5. Single line diagram of the modified IEEE 34-node test system.

5.2. Results and discussion

5.2.1. Sliding weights setting procedure

In order to apply the proposed strategy, at first, the values of the importance factors should be set. Through the introduced iterative procedure, ω_3 was attained equal to $\omega_3^{Opt.} = 0.45$. The tendency curve of the energy hub is found as shown in Fig. 6. Each scenario (S1–S6) in this figure represents two different PHEVs charging load reported to the hub manager. As can be traced in this figure, S5 results in the highest tendency. Based on this analysis, the optimal values of the importance factors should be set equal to $\omega_1^{Opt.} = 0.35$, $\omega_2^{Opt.} = 0.2$, $\omega_3^{Opt.} = 0.45$.

5.2.2. Proposed strategy from the viewpoint of system operator

Setting the values of different importance factors, the PCE runs the proposed multi-criteria charging procedure to attain the optimal charging profiles. Load profiles of Case I–IV during a typical summer day are presented in Fig. 7. As can be seen, the distribution system peak load in Case II is higher than that of Case I. This is indisputable due to the existence of PHEVs in Case II and no coordination scheme in such a case. In contrast, applying Case III as the charging control strategy, even though it imposes no new load to the system during peak hours, creates new peak loads in off-peak hours. Clearly, these new peaks will bring about some problems for the power network, such as investment in higher capacity installations and components. However, by employing the proposed strategy, in bold dotted line in Fig. 7, it can be observed that the charging demand can be efficiently distributed at

Table 1
Different cases defined in this study.

Case no.		Case description		
Case I		A reference system with no PHEV.		
Case II		A system with uncontrolled charging strategy.		
Case III		A system with user-based charging strategy.		
Case IV	Incentive distribution	Prog A (%)	Prog B (%)	Prog C (%)
	Base	17	50	33
	Scenario I	10	10	80
	Scenario II	90	0	10
Case V		A system adopting the profit-based strategy.		

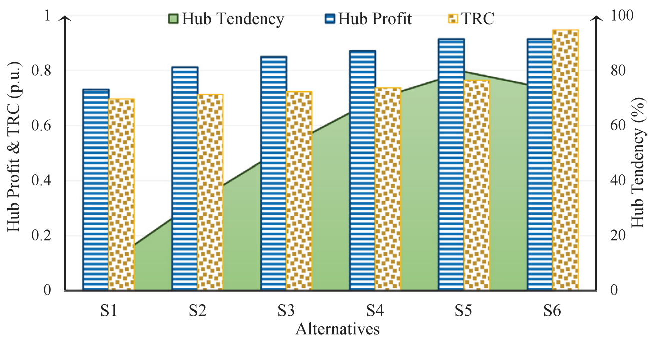

Fig. 6. The energy hub tendency curve.

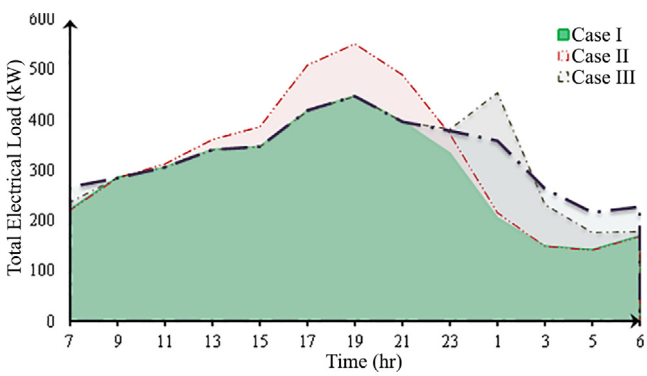

Fig. 7. Load profiles in the various cases.

Table 2
Charging cost of PHEVs for Case III and Case IV.

Different cases	Charging cost (¢)		
	Max	Average	Min
Case III	653.96	231.89	117.63
Case IV	**663.46**	**235.64**	117.63

various times. In other words, this charging control strategy could decrease the peak load by 22% compared to Case III. Therefore, not only would the technical criteria be improved, but also it relaxes or postpones the need for implementing expansion plans aimed to supply this new demand. Besides, as can be seen from this figure, although implementing the proposed method creates a higher peak in the off-pick hours in comparison to Case I, this apex is lower than Case I overall peak value, 420 kWh. Therefore, no expansion schemes for installing new components within the power grid would be needed.

5.2.3. Proposed strategy from the viewpoint of EV owners

Various parameters associated with charging cost of the PHEVs are tabulated in Table 2. As can be seen in this table, the maximum charging cost in Case IV increases compared to Case III. Moreover, the average value of the charging cost in Case IV shows a little growth. Although the customers may need to pay more for charging their vehicles, they will receive some rewards in turn, as presented in Table 3. These rewards can not only compensate the additional cost, but also they offer some revenue for the EV owners.

The other fact, which can be deduced from the results shown in Table 3, is the flexibility that can be attained employing the aforementioned incentive programs. This feature is well reflected in the maximum deviation imposed to the PHEVs participating in **Prog B** and **Prog C** (26.9 kWh). These results ensure that, in line with addressing the main concerns of the network operator and hub manager, the PCE can properly handle the main requirements of the vehicles owners.

Moreover, the maximum level of penalty paid to customers in **Prog A** mirrors this fact that the importance of the technical criterion together with the profit factor forces the optimization procedure in accepting some penalty to satisfy these factors.

In a nutshell, the proposed method not only brings about a high flexibility for the power network but also does not manipulate the charging costs of EVs too much. Besides, it successfully alleviates the peak loads of the network through its incentive scheme.

5.2.4. Proposed strategy from the viewpoint of an energy hub operator

To more deeply investigate the effects of employing various charging control strategies on the amount of profit associated with the energy hub, Case V is defined. The load profile of the test system (lines) and hourly profit of the hub (bars) employing Cases III–V are delineated in Fig. 8. As can be inferred from this figure, the results are approximately identical for time intervals between hours 9–17 when no PHEV charging demand is scheduled. However, as can be traced in this figure, the main differences between the attained profits return to the periods in which the charging control strategy should decide how to dispatch the charging demand, i.e., during hours 21–24 and 1–7. It can be clearly seen from this figure that in Case III, the profit of the hub shows a remarkable decrement compared with the results in Case IV and Case V. On the other hand, even though the proposed control strategy in Case IV takes into consideration many contradictory factors in the PHEVs charging optimization procedure, the obtained profits take similar values compared with the results in Case V. This would again demonstrate the effectiveness of the proposed method which considers conflicting desires as a multi-criteria optimization framework.

5.3. Sensitivity analysis on the incentive programs

To understand the main effects of the introduced incentive mechanism on the prosperity of the proposed strategy, two different scenarios are defined. The obtained load profiles of these two scenarios, together with Case I, are shown in Fig. 9. As can be traced in load profile of Scenario II, there is a significant load

Table 3
Analysis of incentive program parameters in Case IV.

Incentive programs	Penalty cost (¢)		Reward (¢)		Deviation amount (kWh)	
	Max	Min	Max	Min	Max	Min
Prog A	575.9	0	–	–	20.3	0
Prog B & Prog C	–	–	370.2	39.3	26.9	1.15

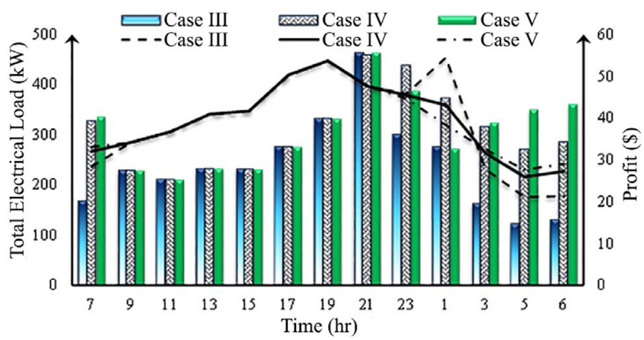

Fig. 8. Profit of the energy hub versus the charging control strategies.

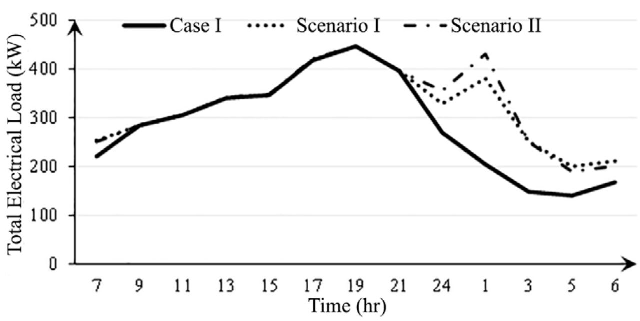

Fig. 9. Load profile of the system versus various incentive contracts.

increase around midnight. In this scenario, most of the EV owners prefer to maintain their desirable charging profiles ($\boldsymbol{PC}_k^{Des.}$) and the introduced incentives are unable to convince them to adopt the PCE's rescheduling programs. Therefore, the PCE is forced to adopt the $\boldsymbol{PC}_k^{Des.}$ and the load profile in the distribution system becomes more similar to the one obtained in Case III.

In contrast, conditions are defined in Scenario I to let the PCE more optimally distribute the required energy for charging in the period between 12 p.m. to 7 a.m. This can be translated to a lower increase in the load around midnight and a more valley-filling profile can be attained. Therefore, one can conclude that if the established incentive mechanism becomes insufficient to motivate the EV owners to participate in the PCE's rescheduling programs, proper control policies by this entity will become fruitless.

6. Conclusion

This paper has presented a multi-criteria PHEVs charging control framework in the context of an energy hub. Attempts were made to meet all the main concerns of PHEV owners and the system operator. This strategy captures the main expectations of the energy hub as a private entity in maximizing its profit in dealing with the charging demand of PHEVs. Besides, the desires of PHEVs' owners can be addressed by implementing the proposed method. Therefore, three different factors, i.e., PHEV owners' convenience criterion, profit factor of the hub, as well as the technical requirements of the power distribution network, were introduced, and the rationale behind them in the proposed strategy was thoroughly discussed. To model such conflicting desires, a multi-objective optimization framework was adopted based on weighted sum method. Besides, an innovative algorithm was developed to effectively involve these factors in the optimization procedure by obtaining the optimal importance weights of each distinct factor in the objective function of the problem. The proposed charging strategy was implemented on a test system, and the results demonstrated that the proposed method could efficiently distribute the PHEVs charging demand over off-peak hours, leading to a maximized load factor, minimized charging costs, and an acceptable level of earned profit for the energy hub. Finally, a sensitivity analysis of the willingness of the PHEVs' owners desires to participate in the proposed charging management schemes was obtained. The obtained results clearly demonstrate the fact that PHEV's owners willingness to participate in such schemes is the critical factor that if not properly addressed, may make any developed framework fruitless.

CRediT authorship contribution statement

Moein Moeini-Aghtaie: Conceptualization, Methodology, Data curation, Validation, Writing – original draft. **Payman Dehghanian:** Methodology, Writing – original draft, Writing – review & editing. **Mehdi Davoudi:** Validation, Writing – review & editing.

Declaration of competing interest

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

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