PHEVs Centralized/Decentralized Charging Control Mechanisms: Requirements and Impacts

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Abstract—**This paper investigates the main features of the PHEV centralized and decentralized charging control mechanisms, their requirements and also impacts on distribution system performance. A home-based charging control scenario as well as a coordinated charging control algorithm for the charging management of PHEVs is devised in this paper. Both the owner preferences and system operator concerns are taken into consideration in an optimization-based framework. The total network losses and charging costs are set as the constraints to the proposed optimization approach. Various aspects of the two mechanisms are discussed and comprehensively compared by their application on the IEEE 34-bus test system. The obtained results and discussions offered demonstrate the efficiency and applicability of the proposed approach in real world.**

I. INTRODUCTION

Petroleum is the primary source of energy used for transportation around the world. As a fossil fuel, its usage releases tons of carbon dioxide and other greenhouse gases into the atmosphere. In addition, growing demand for crude oil has resulted in a drastic rising of energy prices as well as political issues. So, the petroleum usage for running the vehicles is no longer sensible from an economic or environmental viewpoint [1]-[4]. The introduction of electric vehicles opened the door for these advanced technologies to alleviate the strong dependence of this sector on crude oil and its products. The Battery Vehicles (BVs) in the form of either Plug-In Hybrid Vehicles (PHEVs) or all-Electric Vehicles (EVs) have been made as a substitute for the available vehicles. The common characteristic of BVs is their need and dependency to a battery, which is the source of all or part of the energy requisite for propulsion [5], [6].

With the presence of BVs in transportation sector, a transition has been recently sensed from the quite ineffective Internal Combustion Engines (ICEs) to the increased electrification. This, as a result, will alter the energy demand required for transportation purposes from the crude oil to electricity [7]. Among the various technologies available for the electric vehicles, PHEVs have been sensed to be the most common since they offer another great possibility, i.e., to employ an ICE as an auxiliary source for the required power, but still with the electricity as the main source of energy for PHEVs. To serve as an example, a typical PHEV can travel a relatively long distance just with the electric power with an All-Electric Range (AER) of forty or more miles [8]. PHEVs can be recharged if plugging into the power grid when their batteries are depleted. As the number of participated PHEVs increases, more electrical energy required for the charging is requested as a result. The charging control and management issues would, then, be an undeniable concern. In other words, the requirements from the system operator viewpoint and the technical impacts of the PHEVs need to be first answered so that one can be able to gain the numerous advantages of this upcoming technology [1].

In this regard, much research has been conducted to assess the possible impacts of the PHEVS in power systems. Most early works have been dealt with the national impacts of PHEVs [9]. The network and generation capacities, as the main constraining factors for scenarios with massive deployment of the PHEVs, are the main highlighted statements in these works. The investigation done in [10] comes to this conclusion that a very large penetration of PHEVs would place a major stress on peak units. Despite the networks and generation limits on a national level, the local effects onto the electrical grid at distribution level can be even more severe considering the PHEVs' uncontrolled charging. In response, some past works focused on the PHEV penetration impacts on distribution utilities [11]-[13].

Reference [11] examines the impacts of electric vehicle demand on a residential distribution network taking into account various charging scenarios. This study shows that all the charging strategies can create new peak loads seen by a distribution feeder which have to be managed via Advanced Metering Infrastructure (AMI). A basic framework proposed in [12] is applied to different distribution circuits and some

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technical parameters including voltage regulation, transformer loss of life, power losses, and harmonic distortion are attacked. This paper concludes that PHEV penetration rate and distribution issues tend to have a linear relationship. A study in [13] indicates that EVs' load leads to voltage limit violations, higher level of line losses, and also transformer overloads. The authors recommended the integrated planning of network, embedded generation, and EV charging management schemes. The PHEV impacts on the Belgium distribution grid considering the traffic and driving patterns in thoroughly is presented in [14]. With analyzing some real scenarios, this paper comes to this conclusion that the integration of PHEV can deeply deteriorate the power losses and voltage deviations and these impacts cannot be ignored.

Aiming to effectively manage the discussed impacts of PHEVs, some past works in the literature focused on charging control algorithms as the most effective solution highlighting the significance of controlled or smart charging concept [15]-[19]. The existing charging management scenarios can be categorized into two main groups, *centralized* and *decentralized* charging strategies.

- Running the centralized charging strategy, system operators apply a central controller to coordinate the charging patterns of the customers [15]-[17]. Consequently, the operator determines at when and what rate every individual vehicle should be charged [1]. All decisions in this charging management strategy could be made only based on the system-level concerns such as mitigating total losses and feeder congestion, or also taking into account the customer preferences, for example the permissible charging interval, final state of charge (SOC), and charging cost. The controller in these strategies employs power flow studies to distinguish the optimal charging patterns of PHEVs.
- In the decentralized charging strategies, the vehicle owners can directly determine their charging patterns. The electricity price and customer preferences are the main factors determining the charging decisions in this type of charging management procedure [1]. There is no guarantee to reach optimal charging outcome employing decentralized approach from the system operator viewpoint. Anyhow, depending on the electricity tariff mechanism as well as the response behaviors of the electric vehicle owners, the total load of PHEVs may cover the grid requirements.

There has not been, so far, a comprehensive study comparing various aspects of the centralized and distributed charging approaches. In response, this paper examines these two charging control strategies in the context of their requirements, impacts on the power distribution grid and their applicability in real world. In this regard, this paper is structured as follows. The decentralized charging approach is thoroughly introduced in Section II, where a literature survey is conducted and the proposed home-based charging algorithm is investigated. The centralized charging approach is dealt with in Section III where in, following an introduction to the previous efforts, the proposed centralized charging mechanism is introduced. Numerical analysis is conducted in Section IV, followed by the concluding remarks in Section V.

II. Decentralized Charging Approach

The main concept of the decentralized charging strategy, a review on the presented works in the literature, together with the main framework of running a distributed control method in a residential feeder are addressed in this section.

A. Litearture Review

As discussed in the introductory Section, distributed charging control strategy allows each vehicle to choose its charging profile individually. Also, the system operator, only through the electricity tariff, can control the imposed charging load in this approach. Minimal amount of the charging and overhead costs, thanks to the absence of communication infrastructure, is a major advantage of this user-based charging control mechanism, where a smart charging method is implemented in each vehicle. Decentralized charging strategy is still a young field of study and few publications dealing with this approach are addressed as follows.

Reference [1] proposes a decentralized algorithm to coordinate the charging of autonomous PHEVs based on the game theory concept. It is assumed that vehicles are cost-minimizing and they are coupled via a price signal which acts as a control variable in the optimization procedure of charging control problem. This control variable is determined by the average charging strategy of the PHEVs population. The authors in this paper conclude that their decentralized method may lead to a higher PHEVs share in market, especially in cases that centralized strategies become ineffective regarding the customers who wish to independently choose their charging patterns. The decentralized charging algorithm proposed in [20] makes use of the data on the forecasted load and local information about the vehicles such as their plugging interval and SOC. First, the set of individual charging profiles minimizing system costs are determined and then a linear programming (LP) optimization procedure tries to find the optimal solutions. Reference [21] defines a demand-dependent pricing method as a practical strategy which can drive a unique Nash equilibrium, resulting in the valley-filling effect.

B. Home-based Charging Algorithm

In order to more precisely investigate various aspects of the distributed charging algorithms, an optimization model of a home-based charging method will be addressed in the following. Fig. 1 depicts the structure of a home-based charging control procedure. It is assumed that the PHEV charging scheduler in each house run the optimization problem from the customer viewpoint. This problem determines the time and level of charging for the associated PHEVs. The charging cost of PHEV is considered as its main objective function. The charging cost is a function of electricity tariffs and the charging demand as well.

Time-dependent tariffs determined by distribution utility behave as a control variable in PHEVs charging optimization problem from the operator standpoint. It has been shown that time-differentiated pricing models can potentially result in more economical benefits compared to the flat rates.

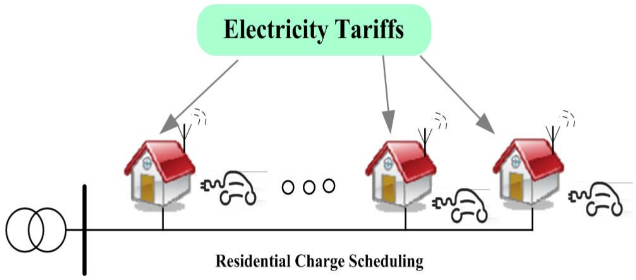

Fig. 1. Home-based charging infrastructure.

Creating smart modifications in the customers' electricity consumption pattern is the basic idea behind the time-dependent pricing methods. Here, the pricing scheme named the time of use (TOU) is taken into consideration.

In TOU pricing model, the electricity price takes different levels within the predetermined time intervals. A three-level TOU tariff can be modeled as follows.

$$\gamma_t = \begin{cases} \gamma_1 & if \ t \in T_1 \\ \gamma_2 & if \ t \in T_2 \\ \gamma_3 & if \ t \in T_3 \end{cases} \tag{1}$$

where, γ_t is the electricity tariff at hour *t*; γ_1 , γ_2 , and γ_3 , respectively, are the level of the OU tariff at off-peak interval (T_1), mid-peak interval (T_2), and peak interval (T_3). It is noteworthy to mention that $\gamma_1 \leq \gamma_2 \leq \gamma_3$ holds.

The PHEV scheduler in each house tries to minimize the total charging cost of the vehicles connected at the outlet section of the house. Consider that we have $\mathbf{PC}_k = [pc_{k,t_s^k},..., pc_{k,t_s^k+i},....., pc_{k,t_f^k-1}] \quad \forall k \in V_h$, pc_{k,t_s^k+i} and V_h which are, respectively, the charging schedule vector of the k^{th} PHEV, the charging level of the k^{th} PHEV at time *t*, and the set of vehicles connected to the house. Also, t_s^k and t_f^k are the plug-in time and departure time of the k^{th} PHEV, respectively. The optimization problem of the PHEVs scheduler in each house can be then modeled as follows.

$$\min \left(\sum_{v=1}^{V_h} \sum_{t=1}^{T} \gamma_t \times pc_{k,t} \times \Delta t \right) \tag{2}$$

$$s.t.$$

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

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

where, $E_k^{Rq.}$ and $PC_k^{\max}$ represent the energy required to fully charge the battery of the k^{th} PHEV and the maximum charging level of the k^{th} PHEV at time *t*. Solving this problem, the optimal charging schedule for the PHEVs at each house can be obtained.

III. Centralized Charging Approach

In this section, the main principles associated with the coordinated charging approach along with its characteristics are reported. Also, the framework of the proposed centralized charging control method is addressed.

A. Related Work

An abundance of research ranging from structure identification to detailed studies has been conducted in the field of PHEVs' coordinated charging. The authors in [22] propose a decision making procedure for the electric vehicle owners. Choosing the way to charge (coordinated by aggregator or uncoordinated) in the viewpoint of vehicle owners is the main contribution of this work. The main conclusion of this paper is interesting since it shows that under certain conditions, depending on the gasoline and electricity prices, the vehicles may decide not to involve in any coordinated charging programs.

The coordinated charging strategy from the perspective of an aggregator is discussed in [23]. In order to reach the optimal charging profiles for the participated PHEVs, the aggregator runs an optimization problem minimizing the operation costs while satisfying the demand of the fleet. Both cases, either the aggregator is a price-taker or it influences the price, are investigated. Although many works have shown that the centralized charging strategy can efficiently alleviate the destructive impacts of the electric vehicles, it is discussed in [1] that the process of achieving a practical centralized charging algorithm in scenarios with high penetration of electric vehicles may become impossible. This condition becomes worse considering those customers who are accustomed to having full authority over their energy consumption patterns. Coordinating many autonomous agents aimed to reach the optimal pattern of the charging is, therefore, a non-trivial task.

B. Proposed Centralized Charging Control Method

The main goal of the centralized charging strategy is to minimize the system overall costs while taking into account both network constraints and customer requirements. As discussed in the introductory Section, the presence of PHEV demands in distribution networks can overshadow the technical parameters of the network, e.g., the total losses and voltage profiles. The authors in [24] demonstrated that the penetration of more PHEVs for the main sake of minimizing the total losses in distribution systems can also minimize the voltage deviations associated with these electric vehicles. Consequently, the total amount of losses of the system in this paper is considered as a technical criterion which has to be minimized in the proposed coordinated charging algorithm. On the other hand, the prosperity of any charging control method is relied on its abilities to cover the needs and requirements of the vehicle owner. Therefore, the total charging cost (TCC) of the PHEVs is introduced as the other main factor which has to be minimized as well in the proposed charging control policy.

Regarding the discussions on the practical and effective coordinated charging policies, the algorithm associated with the proposed coordinated charging scheme is shown in Fig. 2 which includes the main operation steps. At each time, the central PHEV charging scheduler takes the data associated with the connected vehicles, including the permissible charging period, required energy of charging, and the maximum charging level of PHEVs. Then, the scheduler need

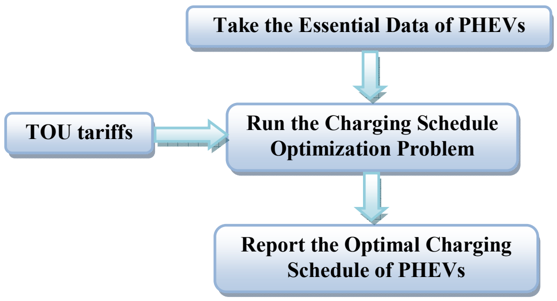

Fig. 2. General flowchart for the propoed coordinated charging strategy.

to run an optimization problem for the determination of the level and time of charging for each PHEV connected.

The optimization model of the proposed coordinated charging algorithm, which seeks the simultaneous minimization of the TCC and total system losses, is formulated as follows.

$$\min \left(\omega_{Losses} \times \frac{Losses_{Tot}}{Losses_{Base}} + \omega_{CC} \times \frac{TCC}{TCC_{Base}} \right) \tag{5}$$

$s.t.$

$$S_{b,t} \geq S_{b,t}^{\min} \qquad \forall b \in B \tag{6}$$

$$S_{b,t} \leq S_{b,t}^{\max} \qquad \forall b \in B \tag{7}$$

$$0 \leq pc_{k,t} \leq PC_{k}^{\max} \quad \forall k \in V \tag{8}$$

$$\sum_{t=t_s^k}^{t_f^k} pc_{k,t} = E_k^{Rq.} \qquad \forall k \in V \tag{9}$$

where, $S_{b,t}$, $S_{b,t}^{\min}$, $S_{b,t}^{\max}$, B, and V respectively represent the load of node b at time t, the minimum load of node b at time t, the maximum load of node b at time t, the set of nodes, and the set of PHEVs. The $Losses_{Tot}$ and TCC are given by

$$Losses_{Tot} = \sum_{t=1}^{T} \sum_{l=1}^{L} R_l I_{l,t}^2 \tag{10}$$

$$TCC = \sum_{v=1}^{V} \sum_{t=1}^{T} \gamma_t \times pc_{k,t} \times \Delta t \tag{11}$$

where, ω_{Losses}, ω_{CC}, $Losses_{Base}$ and TCC_{Base} are respectively the importance factor associated with the total losses, importance factor of the total charging cost, the total losses of the system with no presence of PHEV demand, and the sum of PHEV charging costs attained via the home-based charging control approach.

IV. Numerical Results

To more practically compare various attributes of the decentralized and the proposed centralized charging strategies, some case studies with different PHEV penetrations levels (11.3%, 35%, and 45%) and different charging control strategies are carefully investigated in this Section, as follows.

- *Case 1*: a reference system with no PHEV.
- *Case 2*: a system with uncontrolled charging strategy. In this system, the PHEVs begin the charging process as soon as they return home from their last trip.
- *Case 3*: a system with home-based charging strategy according to the method presented in Section II.
- *Case 4*: a system employing the proposed centralized charging control method.

A. System under Study

In this paper, the IEEE 34-node test feeder is considered as the test system whose single line diagram is as depicted in Fig. 3. Here, this test system is modeled as a residential network. The medium and low voltage levels of this network are respectively 24.9 kV and 230 V. this feeder includes 33 load points, 8 of which are single phase and the remaining ones are three phase loads. It is assumed that each phase of the load point is connected to two houses. Other data on this test system can be found in [25]. The three-level TOU tariff taken from [26] is utilized here as the electric tariffs. This tariff is delineated in Fig. 4.

Running any studies about the PHEV impacts on distribuion network calls for a comprehensve survey on the vehicle owner behaviors. The transportation surveys can be considered as the best source of data on various kinds of vehicles and trip characteristics. The National Household Traveling Data (NHTS) has been introduced as a main reference in electric vehicle studies which provides the essential data for these studies [27]. Different information for the vehicles such as the driving patterns, daily miles driven, the number and types of PHEVs along with the time vehicle plugged into the network, charging level and the time at which the vehicle has to be unplugged employed in this paper is based on the method proposed in [27].

B. Results and Discussion

All the introduced cases (Cases 1-4) with different levels of PHEV penetration (11.3%, 35% and 45%) were simulated on the IEEE 34-node test feeder and the results were obtained. First, the cases 1 and 2 are referred. Figs. 5, 6, and 7 respectively depict the load profile of the IEEE 34-node

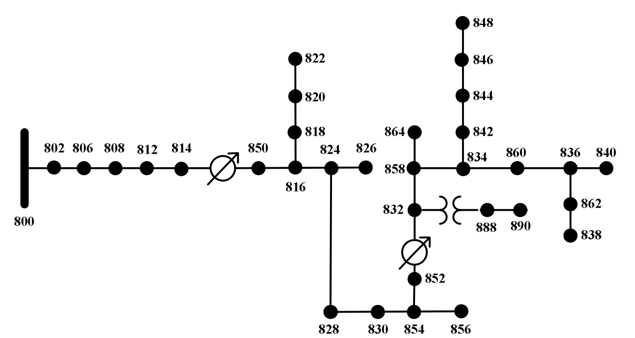

Fig. 3. Single line diagram of the IEEE 34 node test system.

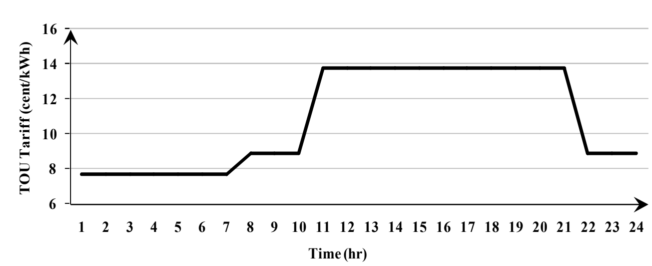

Fig. 4. The three-level TOU tariff.

test feeder for 11.3%, 35% and 45% PHEV penetration levels in a typical summer day considering different charging control strategies. As can be traced in these figures, different PHEV penetration levels in Case 2, which can be distinguished as the worst charging scenario, escalate the peak load of the distribution system compared to that of Case 1. This can lead to the overload of some network assets such as transformers. Therefore, it calls for a systematic charging control to reduce the destructive impacts associated with the presence of PHEV in distribution systems.

A substantial movement can be achieved applying the home-base charging control (Case 2). Applying this control approach, charging during the peak hours will be avoided. However, as the PHEV penetration level grows in the system, this strategy results in the new peak loads in the off-peak hours (see Fig. 7). The new peaks are the result of employing the TOU tariffs. In home-based charging control, as the off-peak hours begin and consequently the electricity tariff decreases, the PHEV schedulers in each home begin the charging procedure. This results a high level of charging simultaneity and therefore imposes a peak almost as high as the on-peak period (especially in 45% scenario). Anyhow, this kind of charging control finds the charging profiles with lowest costs.

Following the results shown in Figs. 5-7, it can be deduced that the centralized charging strategy in Case 4 efficiently has distributed the required energy for charging PHEVs in various times along the period of studies and consequently no new peak load is created there. As a notification, in all the results associated with Case 4, shown in Figs. 5-7, the importance factors of the total losses and the total charging cost are considered to be 0.5 ($\omega_{Losses} = \omega_{CC} = 0.5$). Taking into account the total losses as a main criterion for the objective function in the proposed centralized charging control, it guides the charging demand of PHEVs to the periods associated with the lower total losses in the network. Table I shows the percentage of peak load increments for various Cases with different PHEV penetration levels. It can be easily deduced that Case 3 in scenarios with high level of PHEV penetration, i.e. 45%, becomes unable to eliminate the new peak loads.

In order to compare the capabilities associated with the charging control strategies in reaching the desired charging plans with minimum costs as a main requirement of the vehicle owners, the average values of charging cost for three scenarios of PHEV penetration are calculated and shown in Table II. It can be seen that the proposed centralized charging control method (Case 4) reached the plans with lower charging cost average compare to the home-based charging strategy (Case 3). As the PHEV penetration level increases, the charging cost difference between Case 3 and Case 4 would raise as well.

The values of importance factors in Case 4 can result in different values for technical and economical criteria. Table III represents the results of running Case 4 with different values of ω_{Losses} and ω_{CC} . According to the results shown in this table, when $\omega_{Losses} = 0 \,\&\, \omega_{CC} = 1$, the optimization procedure reaches the results with low level of load factor and total charging cost. This plan can properly satisfy the customer requirements.

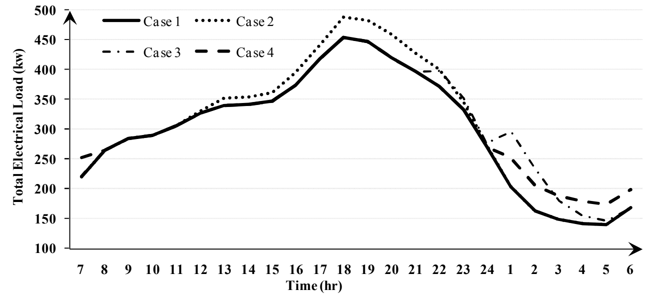

Fig. 5. Load profiles of various charging control algorithms (11.3%).

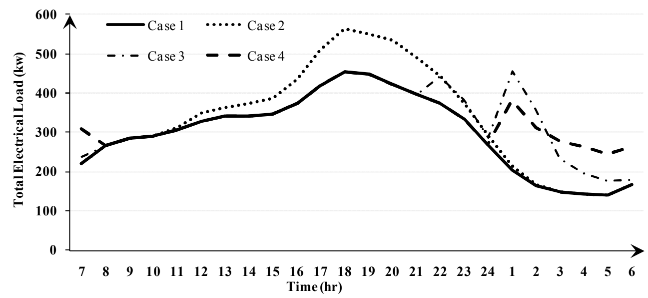

Fig. 6. Load profiles of various charging control algorithms (35%).

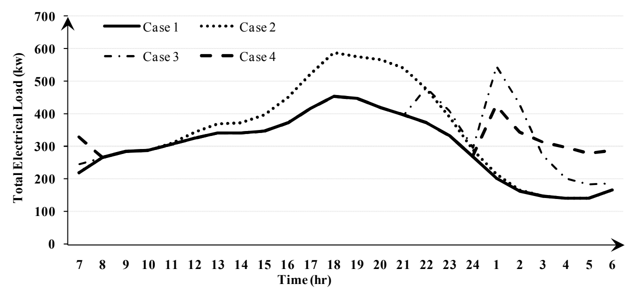

Fig. 7. Load profiles of various charging control algorithms (45%).

TABLE I. REALTIVE INCREMENT OF PEAK LOAD FOR VARIOUS LEVLS OF PHEV PENETRATION

PHEV Pen.	Case 2	Case 3	Case 4
11.3%	7.48%	0	0%
35%	23.82%	0.14%	0%
45%	29.32%	20.48%	0%

TABLE II. AVERAGE VALUES OF THE CHARGING COSTS FOR DIFFERENT PHEV PENETRATION LEVELS (¢)

PHEV Pen.	Case 3	Case 4
11.3%	54.6	53.6
35%	55.6	54.2
45%	56.8	54.9

TABLE III. IMPACTS OF THE IMPORTANCE FACTORS ON THE OBJECTIVE FUNCTION VALUES (CASE 4)

ω_{Losses}	ω_{CC}	TCC[a] (¢)	LF[b]
0	1	6574.6	0.6999
0.5	0.5	6852.6	0.7011
0.8	0.2	8692.1	0.7289
1	0	8715.6	0.7366

[a]: Total Charging Cost   [b]: Load Factor

In contrast, the system oriented factors such as the load factor has improper values and it can be improved choosing some higher levels for the total losses importance factor. Comparing these results with the ones in the third row of this table, i.e. ($\omega_{Losses} = 1 \& \omega_{CC} = 0$), it can be observed that the total charging cost has experienced an increment (2117.5 ¢) while the load factor improvement is 0.0367.

V. Concluding Remarks

This paper has explained the main attributes of the centralized and decentralized charging strategies as the two main classes of smart charging control mechanisms. Aimed to practically compare various aspects of employing these strategies, a home-based charging control method together with a coordinated charging control algorithm is introduced. The proposed coordinated PHEV management policy strives to satisfy the needs, requirements, and preferences of the vehicle owners while ensuring the efficient operation of the distribution system. In this regard, combination of the total losses and total charging cost is considered as the objective functions to this centralized charging methodology. The proposed methods were implemented on the IEEE 34-node test feeder. The obtained results demonstrate that the proposed coordinated charging method can more efficiently allocate the charging energy requirement during the off-peak hours achieving a proper "valley-filling", and leading to a maximized load factor as well as minimized charging costs. Although the coordinated charging control algorithm results in a considerable improvement in the distribution system technical factors, which would be pleasant in the stand point of the system operator, its prosperity depends on the acceptance of the vehicle owners to participate in these charging control plans. Therefore, one can conclude that once the centralized charging control strategy is used as the smart charging procedure, the incentive programs based on the customers' willingness would be inventible. This serves as the authors' next research focus coming soon.

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