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Local and Central Supervision of Optimal Plug-In Electric Vehicles Energy Dispatching for Load Smoothing within the Innovative Smart Grid

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Abstract- This paper deals with optimal Plug-in electric vehicles (PEVs) energy dispatching with electrical grid incorporating cooperative central and local supervision. The Central Supervision Center (CSC) aims to achieve the collaborative power scheduling for numerous Charging Stations (CSs) equipped with PEVs. In the Local Supervision Center (LSC), the PEVs power management has been established to flatten the conventional load for each Charging Station (CS). Consequently, the CSC gathers information taking into account various constraints, including the load of the respective CS and neighboring CSs, the availability of PEVs at the considered CS and among PEVs' neighbors, the initial State Of Charge (SOC) of the PEVs connected to the respective CS and that of PEVs' neighbors, as well as the allowable lower and upper limits for PEVs battery SOC as inputs data. We considered a simulation of the conventional power for three studied CSs in which the supervision strategy appropriately collaborates among them to guarantee their power smoothness thanks to the bi-directional PEVs energy management. The results highlight the load power improvement achieved by valleys filling and peaks shaving in each CS power profile through four distinctive operating modes. Compared to existing methods in the field, these outcomes reveal the effectiveness of this approach in reducing power fluctuations, achieved through both LSC and CSC, with the goal of alleviating stress on the smart grid. While incentivizing the PEVs integration and Vehicle-to-Grid (V2G) profits, dynamics, lifetime, and cost modelling of PEVs batteries might be included into future studies to enhance their charging process.

Keywords Plug-in Electric Vehicles (PEVs), energy dispatching, central and local supervision, Vehicle-to-Grid (V2G), smoothness.

1. Introduction

During recent years, one of the principal environmental concerns in developing nations has been the escalating problem of pollution which is menacing the environmental human society growth. Indeed, the pressing issues pertaining to energy shortages and the phenomenon of global warming have given rise to significant steps to tackle these concerns through various regulation and motivations including the reduction of greenhouse gas emissions and fossil fuel dependency, as well as the promotion of energy conservation and the utilization of sustainable energy sources, among others [1, 2].

Recently, numerous incentives for the development and the commercialization of electrifying the transportation area have attracted steadily growing interest around the world [3]. Significantly, study in [4] has investigated the massive adoption of Plug-in Electric Vehicles (PEVs) as an outstanding and famous electric vehicles category. These vehicles hold the promise of considerably enhancing energy security, improving energy conversion efficiencies and reducing greenhouse gas emissions.

In an attempt to integrate PEVs into the smart grid's communication and control framework, various existing research efforts are devoted to concentrate on the smart grid infrastructure, ideal PEVs integration, coordinated PEVs charging/discharging processes and optimal V2G implementation [5, 6]. Recently, researchers in Ref. [7] have focused on assessing the impacts of electric vehicle charging within the framework of electricity market actions. This investigation aims to demonstrate the impact of electric vehicle charging profiles reducing costs, optimizing power dispatch, and promoting renewable energy utilization while lowering emissions. A study in Ref. [8] has emphasized an innovative event-triggered scheduling scheme for V2G process. This method involves the context of stochastic PEVs connections to an intelligent grid using mathematical model formulation with assembling input data. These works are of commendable quality and have achieved valuable insights into the issue of PEVs charge scheduling, smart grid technology and V2G notions. Indeed, study in Ref. [9] have adapted a multi-objective optimization method of PEVs within low voltage distribution networks. The primary objectives of this approach include reducing the charging expenses through the application of a weighted sum technique and fuzzy control. Moreover, the secondary goals involve mitigating voltage drops and disturbances resulting from these actions. The recent investigation highlighted in Ref. [10] has brought attention to an innovative dispatching scheme for V2G aggregators in auxiliary frequency regulation, taking into account both PEV driving needs and the aggregator's inherent benefits. But it’s crucial to acknowledge that these studies don’t focus on the minimization of the base load power peak intensity and the achievement of energy balance. Therefore, authors in Ref. [11] have dealt with a flexible control scheme applying controlled charging of PEVs which operate in seven modes to ensure efficient energy organizing for flattening load power curve within smart grid infrastructure. Nevertheless, they don't take into account the flexibility of the number of PEVs to be connected on a large scale. For these targets, work in Ref. [12] has introduced a central controller model for PEVs, designed to enhance the PEVs power attribute and their involvement within the power market. This method has incorporated a Particle-Swarm-Optimization (PSO) approach appointed into two layers. Research in Ref. [13] has elaborated a multi-objective optimization framework within smart cities context taking into consideration the advantages of multiple stakeholders implicated in smart charging and discharging of PEVs. Although these methods have offered significant solutions, they do not consider the time of PEVs identification, the charging during and the priority order of each PEV. In that, authors in Ref. [14] have explored an effective approach for filling valleys in the context of centrally coordinated charging for a significant fleet of electric vehicles in which the charging priority indicator and the capacity margin are introduced. The method is employed to identify time periods during which the grid offers surplus energy for electric vehicle charging, while the latter establishes the order in which electric vehicles are charged during each time period. A predictive control model based on computational solution and applied to smart grid featuring multiple electric vehicles charging stations has been studied in Ref. [15]. These suggested approaches have made appreciated methods in tackling energy balance challenges within smart grid. However, it's asserted to highlight that the cooperative coordination among distinct PEVs and charging stations remains underexplored.

Compared to previous approaches, examining the correlation among various charging stations, charging infrastructure, and PEVs bidirectional power transaction could be contributory in ensuring an enhanced energy balance and a more regular total load power profile.

The key objective of this study is to address the significant gaps mentioned earlier, by establishing a novel approach for scheduling PEVs in a smart distribution grid. Thus, this approach can be applied to any Charging Station (CS) as part of smart grid infrastructure regardless of the number of PEVs it is equipped with. Indeed, this study deals with central and local supervision with the objective of recognizing an efficient power distribution for PEVs within a smart grid structure. Our considered system comprises three Charging Stations (CSs). The control strategy explored in this paper involves the exchange of data joining the electrical grid and each CS to establish an adequate bi-directional PEVs energy exchange. To satisfy an improved balance between energy demand and supply and to attain a more consistent load demand, both Local and Central Supervision Centers for the CSs units were established. In the Local Supervision Center (LSC), the bi-directional PEV power command has been established on the way to flatten each CS conventional load power taking into consideration the conventional load power of each corresponding CS and all their PEVs accessibility. The target is to guarantee an efficient power scheduling for the proper charging and discharging process of their PEVs. The Central Supervision Center (CSC) coordinates energy management with each LSC according to the CS neighbors’ conventional power availability, PEVs’ neighbors’ power and charging posts availability. Thus, in this strategy, various PEV power services, cooperative energy management, conventional load power as well as PEVs availability issues are concurrently taken into consideration. In comparison to previous research, this method is adaptable to any smart grid, accommodating a flexible number of PEVs. To provide a clearer view, the key contributions of this study are outlined as follows:

- Elaborating an optimal power dispatching management between PEVs and smart grid ensured by both LSC and CSC. Indeed, the CSC will transfer the necessary information to each LSC which controls the load power of the corresponding CS according to a supervision strategy.
- Detecting the required bidirectional power exchange for each PEV to operate optimally in Vehicle-to-Grid (V2G) and Grid-to-Vehicle (G2V) techniques.
- Adjusting each CS conventional demand profile according to four distinct operational modes aiming to peak load intensity decreasing by supplying power to the grid from CS or CS neighbors’ or to

fill valleys by storing the necessary electricity from the main grid in instances of excess or insufficient in the base demand, respectively.

- Achieving a flattened load power profile for each studied CS thanks to the cooperation and power dealing between the considered CS and its neighboring CSs, enhancing therefore the overall power grid efficiency.
- Controlling the State Of Charge of each PEV battery by preventing deep discharge and overcharge, with the goal of enhancing the lifespan of the PEV batteries.

The rest of this research is structured across four sections. Indeed, Section 2 displays the system structure with a detailed overview of the LSC and the CSC. The elaboration and the management of the suggested Charging Station strategy are elucidated in Section 3. Finally, simulation outcomes and conclusions overview are highlighted in Section 4, and Section 5, correspondingly.

2. Studied System Configuration

As the importance of the new architecture of Grid-to-Vehicle (G2V) and Vehicle-to-Grid (V2G), which continue to rise within the perspective of smart grid, our study motivation is establishing a smooth conventional load for several charging stations. This objective is undertaken through the synchronized vehicles charging and/or discharging actions from and/or to the grid, correspondingly. This current study elaborates a shared energy management approach for CS that involves interaction with neighboring CSs units. Fig.1 exhibits a schematic description of the system configuration.

The studied structure is made up of a combination of three CSs, with each CS subsystem comprising ten individual charging posts. Charging posts that share proximity, such as those sited in the same avenues, within a shared parking zone, or within a common residential area, or associated with a communal node transformer, are considered within the same CS. The control of CS load power is ensured by two supervision units. The LSC receives the information about the corresponding CS, its base power demand and their PEVs availability in order to adjust its proper conventional load profile.

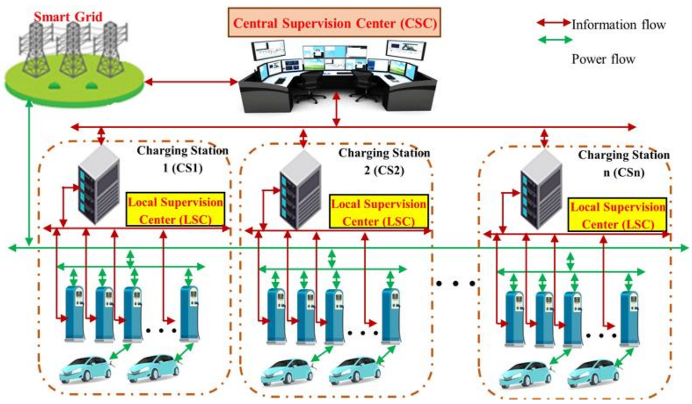


Fig.1. Description of system configuration.

The CSC coordinates energy management with each LSC according to the CS neighbors' conventional power availability, PEVs' neighbors' power and charging posts availability as a whole targeting to achieve the best load profile smoothness and diminish the overall load power variance.

2.1. Central Supervision Center (CSC) Overview

The Central Supervision Center (CSC) serves as an intermediary between the corresponding CS and the neighboring CSs units. The CSC targets to accomplish a smoothed conventional load profile and alleviate burden on the existing power grid. Indeed, the CSC gathers information of all CSs, conveys essential data to each LSC, invents the most efficient operational power schedule for each CS, manages instantly the bi-directional power flow and orchestrates power management with each LSC based on neighboring CSs power availability, PEVs' neighbors' accessibility, their power status and charging post disposal.

Within the smart grid framework, successful two-way communication and exchanged information enable cooperative power management involving PEVs, CS, and CSs neighboring units. This collaboration is performed with smart metering infrastructure which plays a crucial role in efficiently gathering data on energy consumption or generation that's connected to the grid, sending information and accepting instruction to ensure the establishment of an optimal power exchange for all CSs, aiming to achieve a greatly smoothed power demand [16, 17].

2.2. Local Supervision Center (LSC) Overview

Each CS functions with its dedicated Local Supervision Center (LSC) which manages the load power of the corresponding CS according to its base power demand, PEVs availability, connection and disconnection moment, parked time duration and power charging/discharging limits. For that, the two-way data communications among PEVs, CS constraints, charging posts and electrical grid, are crucial. The LSC ensures the acquiring and the processing of input data. Based on that, it plans and generates the optimal charging or discharging action for each charging post to manage the power transaction involving PEVs and electrical system bonded by the considered charging post joining, therefore, undertake the G2V or V2G transactions. Our work's goal is smoothing out the conventional load profile of each CS thanks to leveraging the integration of a huge number of electric vehicles and the widespread existence of charging posts, effectively filling in low-demand periods and reducing high-demand intervals. Consequently, the LSC should be aware regarding the availability of charging posts for joining G2V and V2G operations. Besides, the essential charging-planning parameters are necessary for efficiently gathering, building data and maintaining comprehensive records for each charging post. So, key data should be recorded to LSC such as: the unique identifier of the charging post, its location, its accepted upper power, its accessibility status (the charging post is accessible for public or private use). Furthermore, the LSC should get enough information on the PEVs and the electric vehicle people's needs such as: each PEV unique identifier number "PEV_{nb}", its type "PEV_{type}", its battery model "PEV_{mod}", its battery capacity "PEV_{cap}", the authorized upper "SOC_{upper}" and lower "SOC_{lower}" threshold for PEV Li-Ion battery, the moment when the PEV plugged-in to the grid, the moment when the PEV plugged-out from the grid "T_{out}", the place or zone where the supposed PEV will be stationed and where it requests the LSC to assign the suitable charging post identity, its specific charging post to which this PEV will be related to adequate CS, the starting State Of Charge for the considered PEV battery "SOC_{in}" and the necessary PEV battery SOC value upon the disconnection of this PEV from the grid. For the successful PEVs integration and optimal ensuring the bi-directional power capabilities, each PEV involves advanced battery packs. Considering the battery as the essential electrical part for the efficient PEV penetration, Li-Ion (lithium-ion) battery technology has emerged as a widely adopted technology, making them its optimal selection within the automotive sector owing to its major attributes, such as significant specific power, weighty voltage, extended lifespan, safety features, lightweight design and negligible charge wastage [18-20]. The arrangement of several modern cells of Li-Ion which are associated in parallel and series for battery packs enables the determination of the overall current and voltage requirements [21]. To perform the two-way power transfer, the PEV charging and discharging behaviour is entangled with Tremblay model for Li-Ion battery which is based on a series grouping of a voltage source with an internal resistance as shown in Eq. (1). Eq. (2) and Eq. (3) indicate the characteristic equation of the voltage source of lithium-ion battery for charging and discharging procedures, respectively. Eq. (4) describes the battery State Of Charge. Besides, the battery packs operation must be limited by the SOC restraints to guarantee that the considered Li-Ion battery does not become excessively charged or completely discharged as shown in Eq. (5). Absolutely, the PEV Li-Ion battery SOC value must be managed with consideration to its lower and upper boundaries selected within the range of 20% and 80% to safeguard the battery's dynamic performance and its optimal functioning [22]. Likewise, Eq. (6) fixes a PEV power charging and discharging restriction with consideration to its least essential power to be drawn from the electrical grid "P_{min}" and its higher essential power to be transferred to the power system "P_{min}". In fact, the G2V and V2G technique is performed by the following Eqs [11, 22]:

$$U_{batt}= V_{batt}-R.i \qquad (1)$$

$$V_{batt,ch}= U_0-K.\frac{Q}{i.t-0.1Q}i^*- k\frac{Q}{Q-i.t}i.t+ A.e^{-B.i.t} \qquad (2)$$

$$V_{batt,dich}= U_0-K\frac{Q}{Q-i..t}i^*- k\frac{Q}{Q-i.t}i.t+ A.e^{-B.i.t} \qquad (3)$$

$$SOC(\%)=SOC_{in}(\%)-100*(\int i.dt/Q) \qquad (4)$$

$$SOC_{lower}\leq SOC_{PEVCS}\leq SOC_{upper} \qquad (5)$$

With: SOC_{lower}=20%, SOC_{upper}=80%

$$P_{min}\leq P_{PEVCS}\leq P_{max} \qquad (6)$$

Which:

U_{batt} shows the battery voltage, V_{batt} represents its voltage source, R signifies the internal resistance, $V_{batt,ch}$ characterizes the voltage source for charging process, $V_{batt,dich}$ indicates the voltage source for discharging process, U_0 denotes the battery constant voltage, K symbolizes the constant polarization, A designates the exponential zone amplitude, B terms the exponential zone inverse constant time, Q describes the battery capacity, i illustrates the battery current, i* shows the filtered current, i.t implies the real charge, SOC(%) represents the State of Charge of the PEV battery, SOC_{in}(%) corresponds to the initial state of charge, SOC_{lower} indicates the tolerable minimum battery SOC, SOC_{upper} denotes the tolerable maximum battery SOC, P_{PEVCS} is the required power of the PEV within the corresponding CS, P_{min} exhibits the allowable minimum PEV power and P_{max} defines the allowable maximum PEV power. The properties of the Li-Ion battery are revealed in Table 1,

Table 1. The investigated PEVs battery properties values.

Properties	Value
U_0	3.366 V
R	0.01 Ω
K	0.0076 Ω
A	0.26422 V
B	26.5487 $(Ah)^{-1}$

3. Charging Station Energy Supervision Strategy

For an effective V2G performance in these studied CSs, the proficient handling of charging and discharging activities for electric vehicles which are located at different CS is of paramount significance. For this target, the flowchart of the proposed CS power supervision approach is presented in Fig.2. Moreover, in this study, the relationship, power interaction between CSs neighboring, PEVs energy cooperating and two-way power transaction between PEVs and grid can be extremely encouraged to guarantee a regulated power curve. This involves determining the necessary PEV power parked at the proper CS or the coordinated bi-directional power of PEV parked at neighbors CSs taking into consideration the conventional power demand of neighboring CSs and their PEVs neighbors' accessibility to be either stored from or supplied to the grid, depending on the demand situation. As a result, this energy control seeks to achieve peak reduction and off-peak energy filling for the conventional load power of each CS. For that, four operation modes can be established: CS power already improved, CS power unimproved, CS power local control or CS power central control. This would aim to perform the following goals:

- Detecting the presence of PEVs, indicating the connection and disconnection moment to the appropriate CS, and identifying if there is an excess or lack in CS load power demand.
- Coordinating the required PEVs power charging or discharging quantities for the considering CS as well as cooperating with the PEVs of neighboring CSs, considering factors such as the overall power consumption of neighboring CSs, their PEVs

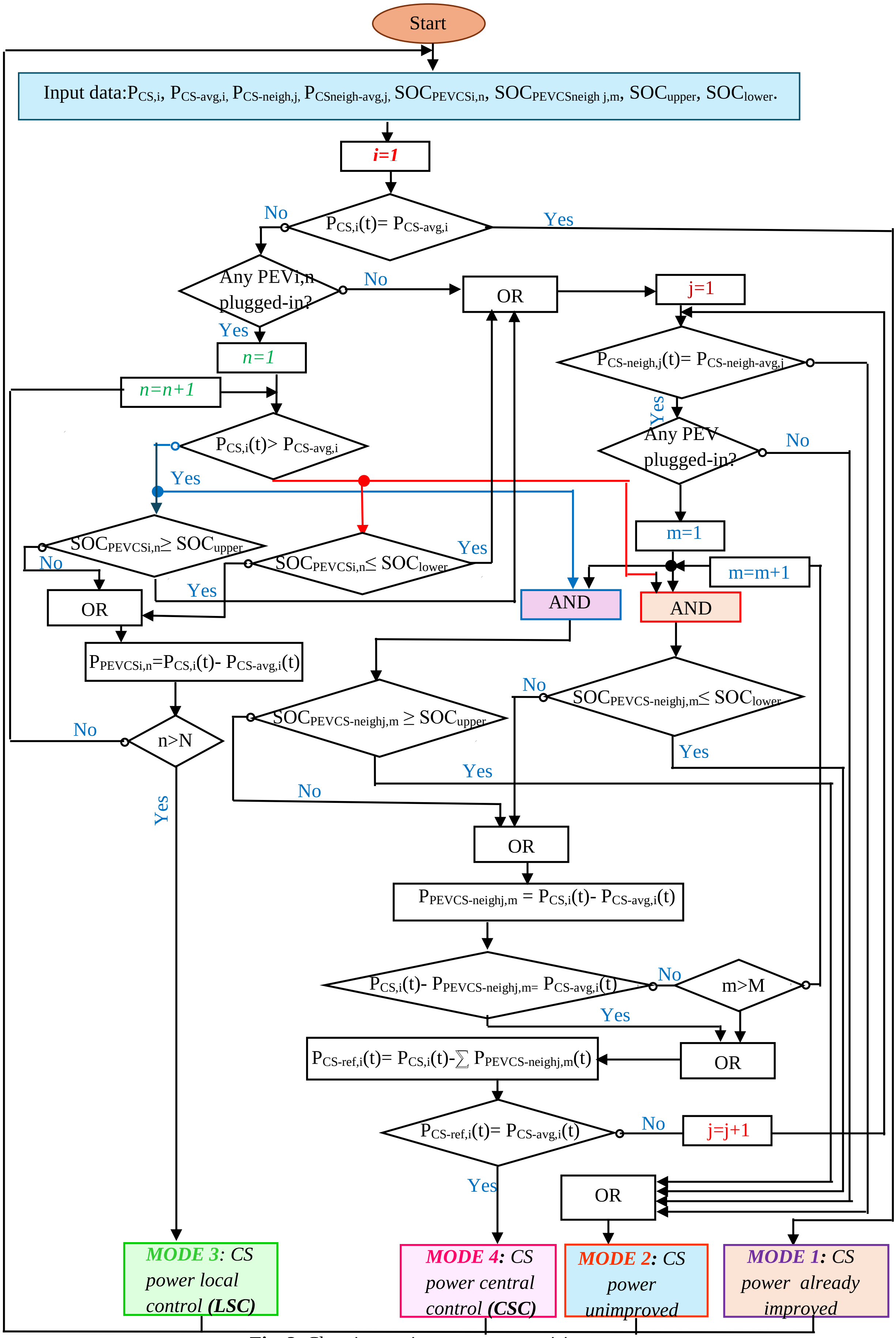


Fig. 2. Charging station energy supervision strategy.

capacity to absorb or provide power to the specified CS and the battery energy starting rate of each neighboring vehicle.

- Reducing fluctuations of each CS conventional load curve by filling demand valleys through storing the PEV its reference power from the CS particularly during lower demand situation (in the event of CS insufficient consumption) and decreasing peak loads within its base load profile by feedbacking the PEV its reference power to the CS solely during peak time-periods (in the event of CS excess consumption). Thus, striving for a rapid achievement of a regular profile.
- Managing the individual PEVs battery SOC energy aiming to maintain it within an acceptable operational range, thereby raising the battery's lifespan.

In fact, each LSC ensures the bi-directional power transactions within its considered CS. Certainly, the proposed control algorithm receives the mandatory information to ascertain the adequate operating mode aiming to assure equilibrium between energy demand and supply for each studied CS within the smart grid framework. Therefore, the CSC relies on data gathered from each LSC to effectively manage, coordinate and adjust the power transmission among CS and its neighboring in order to ameliorate the total variations of CS power curve and make it more regular performing an optimal V2G and G2V evolution. To undertake these targets, the suggested CS supervisory approach takes the following information as inputs:

$P_{CS,i}(t)$	The conventional power demand of the CS "i".
$P_{CS\text{-}avg,i}$	The considered CS "i" average power.
$SOC_{PEVCSi,n}$	The starting SOC of the PEV number "n" for the considered CS, $n \epsilon [1, N]$.
$P_{CS\text{-}neigh,j}(t)$	The conventional power demand of the neighboring CS "j", j ϵ[1, CSneigh]
$P_{CS\text{-}neigh\text{-}avg,j}(t)$	The neighboring CS average power.
$SOC_{PEVCS\text{-}neigh,m}$	The starting SOC of the neighboring PEV number "m" of the CS "j", m ϵ[1, M].
SOC_{lower}	The permitted lower restrictions for Li-Ion SOC of PEVs.
SOC_{upper}	The permitted upper restrictions for Li-Ion SOC of PEVs.
N	The whole electric vehicles number within the investigated CS.
M	The whole neighboring vehicles within the neighboring CS.
CSneigh	The overall number of neighboring

Afterwards, to manage the conventional load of each studied CS, there are four functional modes explained in the following subsections as below:

- ***MODE 1:*** *CS power already improved*

This mode is approved if the conventional power demand of the CS "i", $P_{CS,i\ (t)}$ is identical to the average power of the studied CS "$P_{CS\text{-}avg,i}$". In this state, the CS load remains untouched and the CS reference load "$P_{CS\text{-}ref,i}$ (t)" is done by Eq. (7):

$$P_{CS\text{-}ref,i}(t)= P_{CS\text{-}avg,i} \quad (7)$$

Which: $P_{CS\text{-}ref,i}(t)$ denotes the reference power of the respective CS, $P_{CS\text{-}avg,i}$ represents its average power, and "i" identifies the number of the CS.

- ***MODE 2:*** *CS power unimproved*

This mode is detected if one the following scenarios is active:

-There are no PEVs parked at the proper CS_i, the PEV_n connected at the considered CS attained the maximum "SOC_{upper}" or the minimum "SOC_{lower}" SOC battery restraints and the neighboring CS conventional power demand is not within an improved power range.

-There are no parked PEVs at the neighboring CS_j.

-The neighboring PEV_m has been connected to CS, but the charging/discharging transactions is not initiated due to neighboring PEV reaching its upper battery SOC limits SOC_{upper}" indicating its full charge, or attainment its lower battery SOC limits "SOC_{lower}" indicating its full discharge.

According to these scenarios, no power is switched with the CS and its neighbors, meaning that the reference power of the PEV_n of the studied CS_i is: "$P_{PEVCSi,n}$=0" and the reference power of the PEV_m of the neighboring CS_j is: $P_{PEVCS\text{-}neigj,m(t)}$=0. As a result, the studied CS_i load remains unaffected, and Eq. (8) presents the CS load power $P_{CS\text{-}ref,i(t)}$:

$$P_{CS\text{-}ref,i}(t)= P_{CS,i} \quad (8)$$

Which: $P_{CS,i}$ signifies the CS conventional power.

- ***MODE 3:*** *CS power local control*

This mode is achieved when the PEVs belonging to the respective CS are connected and available for either G2V or V2G techniques. If the conventional power demand of the studied CS_i denoted as "$P_{CS,i}(t)$" is less than the average power of CS_i "$P_{CS\text{-}avg,i}$" and the PEV_n battery SOC is lower than the SOC_{upper}, then the PEV_n of the proper CS_i keeps energy to contribute for energy balance and demand shortfall within time-intervals of lower demand (PEV Charging action: G2V technique). On the other hand, if "$P_{CS,i}(t)$" surpasses $P_{CS\text{-}avg,i}(t)$ and the PEV_n battery SOC is higher than the SOC_{lower}; thus, the PEV_n of the proper CS_i is operated to provide power to the electrical system within time-intervals of elevated demand and contribute to reduce the excess in demand (PEV discharging action: V2G technique). Considering this situation, the reference PEV_n power is given by: "$P_{PEVCSi,n}(t)= P_{CS,i}(t)- P_{CS\text{-}avg,i}$". If all PEVs connected to the considered CS_i participate in CS energy management as well as power curve regulation, so, the LSC is performed and the CS reference power "$P_{CS\text{-}ref,i}$" is presented by Eq. (9):

$$P_{CS\text{-}ref,i}(t)=P_{CS,i}(t)-\sum P_{PEVCSi,n}(t), \quad n \epsilon [1, N] \quad (9)$$

Which: $\sum P_{PEVCSi,n}(t)$ signifies the total power of all PEVs within the considered CS.

- ***MODE 4:*** *CS power central control*

This operating mode is acquired if the following circumstances are realized:

- No PEVs from the corresponding CS_i are currently parked.
- The PEV related to the studied CS_i has attained either the upper "SOC_{upper}" or the lower "SOC_{lower}" battery energy levels signifying full charge or complete discharge, respectively.
- Neighboring CS exists, and the neighboring CS conventional load is within the desired average power state ($P_{CS\text{-}neigh,j}(t)= P_{CS\text{-}neigh\text{-}avg,j}(t)$)
- There are PEVs parked at neighboring CS. As the result, if the CS_i conventional power demand "$P_{CS,i}(t)$" is less than its average power "$P_{CS\text{-}avg,i}(t)$" and the SOC Li-Ion battery of CS neighbor's PEV is lower than the "SOC_{upper}", then the energy storage from CS_i is performed by a neighboring PEV (G2V operation via neighboring PEVs). Otherwise, if "$P_{CS,i}(t)$" is more than "$P_{CS\text{-}avg,i}(t)$" and the SOC rate of Li-Ion battery of the neighboring PEV is higher than "SOC_{lower}", subsequently there is an extra-consumption within the considered CS_i which should be decreasing via the neighbor's PEV (V2G operation via neighboring PEVs).

Based on these circumstances, the reference power of neighbor's PEV is stated as:
"$P_{PEVCS\text{-}neighi,m}(t)= P_{CS,i}(t)$- "$P_{CS,i}(t)- P_{CS\text{-}avg,i}(t)$", if the total number of neighboring PEVs joins optimally the V2G and G2V process, the CS reference load "$P_{CS\text{-}ref,i}(t)$" is displayed Eq. (10):

$$P_{CS\text{-}ref,i}(t) =P_{CS,i}(t)-\sum P_{PEVCS\text{-}neigh,m}(t) \qquad m \in [1, M] \qquad (10)$$

Which: $\sum P_{PEVCS\text{-}neigh,m}(t)$ implies the total power of all PEVs neighbors' within the neighboring CS.

If CS conventional load was not yet enhanced, alternative neighboring CS should be considered. Accordingly, if all neighboring CSs have participated in the CS power demand flattening, the CSC is successfully accomplished and the CS reference load "$P_{CS\text{-}ref,i}(t)$" is established by Eq. (11):

$$P_{CS\text{-}ref,i}(t)= P_{CS,i}(t)-\sum\sum P_{PEVCSneighj,m}(t)$$
$$m \in [1,M], j \in [1, CSneigh] \qquad (11)$$

Which: $\sum\sum P_{PEVCSneighj,m}(t)$ indicates the total power of all PEVs neighbors' of all neighboring CSs.

4. Simulation Results

The proposed supervision approach was verified during the day which was split into 96 intervals. Specifically, the data for one day cycle and the results of simulations are tested at each 15min time slot. To thoroughly prove the effectuality and the usefulness of the established energy supervision for numerous CSs, a simulation of three studied CSs was carried out to perform the cooperative power exchange among all elements within the system according to the LSC and CSC scheduling. The objective is to regulate the overall demand of each studied intelligent CS and achieve its utmost level of smoothness corresponding to the distinctive operating modes, simultaneously manage the bi-directional PEVs power service scheduling of the proper CS and its neighbors.

The obtained results are involved taking into account the specific conventional power profile of each CS, its average power, the PEVs inputs data and their constraints. Indeed, Fig.3 presents the base daily load power profile for three distinct CSs. Notably, these profiles display several fluctuations which are further exacerbated by uncoordinated PEV charging services. This situation leads to a substantial surge in demand, thereby could create an additional threat to electrical distribution, pose harmful impacts on power quality and potentially threaten power system stability.

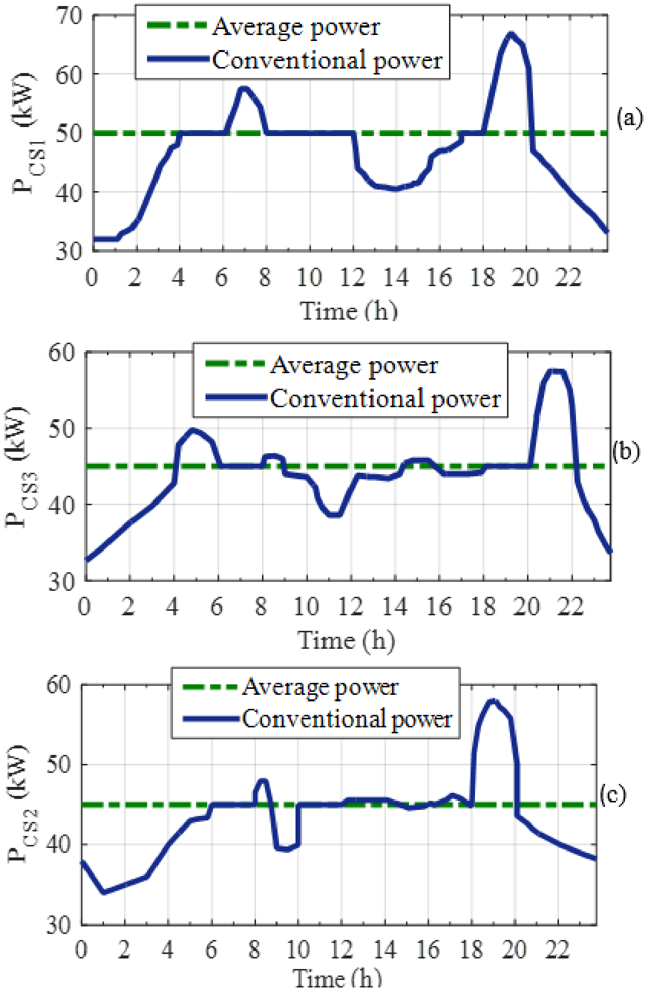


Fig. 3. Base power profile of charging station "i": (a)CS1, (b)CS2, (c)CS3.

Fig.4 shows the distribution of PEVs across various connection time slots and parking at its suitable CS_i, considering a total of ten PEVs for each analysed CS. We considered that each PEV arrives at the corresponding charging post, workplace, parking lot belonging to the same CS at each time interval accompanied by their defining attributes, charging details data, and initial conditions. Various types of PEVs are considered, each equipped with specific battery capacities such as 14 kWh, 11 kWh, 20.4 kWh and so on. Within this study, the permissible lower and upper thresholds for the studied Li-Ion battery SOC are maintained at 0.8 and 0.2 respectively. Additionally, their adequate maximum power injection into the grid is set at 2 kW, while the minimum power storage from the grid is set at -2 kW.

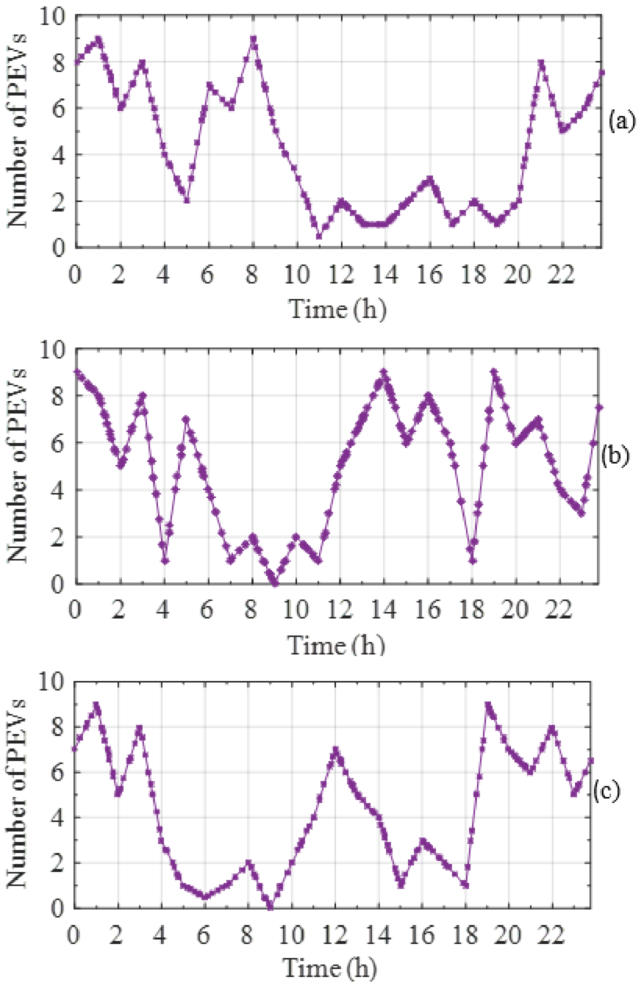


Fig. 4. PEVs distribution across various parking time slots at the suitable CS_i: ((a)CS1, ((b)CS2, (c)CS3.

Fig.5 displays the total PEVs exchanged power with three CSs. Notably, the cumulative participation of all PEVs associated with each CSi plays a crucial role in enabling either local or central power control over the load demand of the studied CS. This control is achieved through the combined implementation of G2V and V2G operations. According to the convention chosen and the adequate selective mode, each PEV stores energy from the grid during time slots of consumption scarcity, typically occurring during off-peak periods, thus ensuring the operation of charging the PEV battery (confirming G2V procedure) and denoting negative PEVs powers. Additionally, these electric vehicles contribute to afford electrical system from energy during periods of power utilization surplus, normally during peak periods, consequently guaranteeing the operation of discharging the PEV battery (confirming V2G procedure) and denoting by positive PEVs powers. Fig.6 and Fig.7 present the charging scheduling of two selected CS1 and CS3 in which the PEVs charging services offered at charging post 7 and charging post 4, respectively. These two charging posts are designated to provide distinct charging establishments throughout the day, respectively.

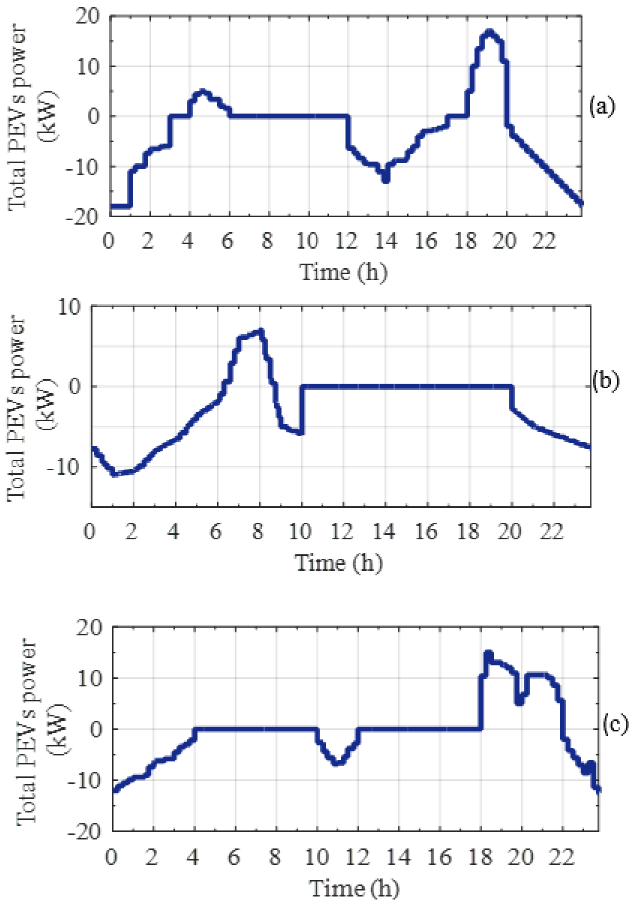


Fig. 5. Total PEVs power profiles of studied CSi: (a)CS1, (b)CS2, (c)CS3.

The upper portion of each graph shows the resulting power supplied by the respective charging post. It is remarkable that the charging and discharging organizations for the connected PEVs can be ensured, while also achieving a more stable load curve for each studied CS. Notably, the lower section of each graph illustrates the profile of the PEV battery SOC for the relating charging post and confirms its charging and discharging behaviour. It is important to note that the discharging action is characterized by a decrease in the SOC value.

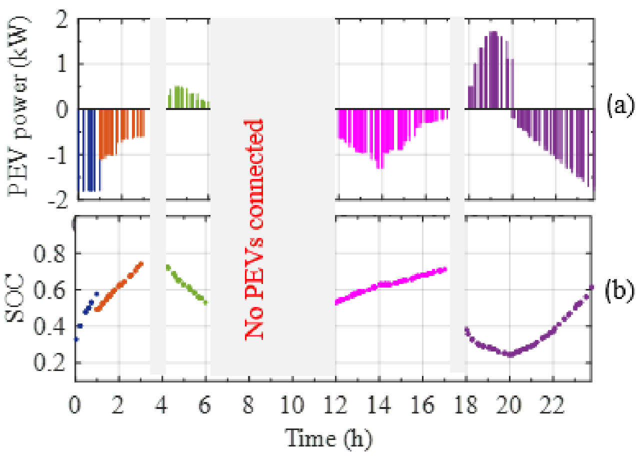


Fig. 6. PEVs charging services offered at charging post 7 of CS1: (a) PEV power, (b) SOC.

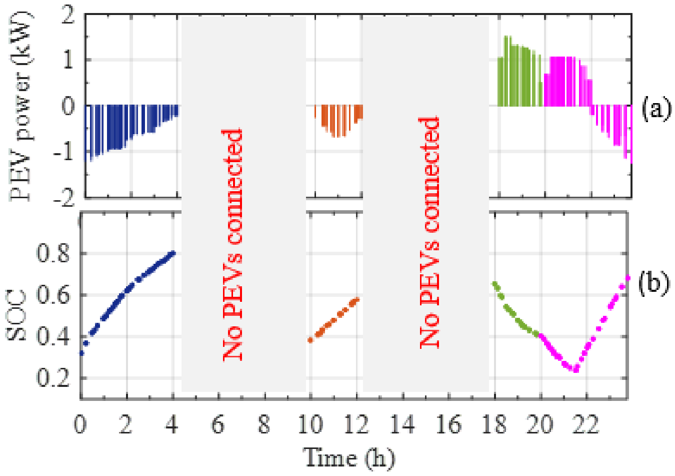


Fig. 7. PEVs charging services offered at charging post 4 of CS3: (a) PEV power, (b) SOC.

The organization of charging profile for two vehicles situated at CS2 is described in Fig.8. Notably, PEV1 plugs into CS2 at the 32th time interval with an initial SOC^{in} of 0.62. After that, this PEV will be plugged out from CS2 at the 40th time interval with a final SOC^{out} of 0.71, and its Li-Ion battery capacity is 14 kWh. PEV2 joins the CS2 at the 80th time interval with a starting SOC^{in} of 0.58. It disconnects at the 96th time interval, with an SOC^{out} of 0.8, and its corresponding battery capacity is 20.4 kWh.

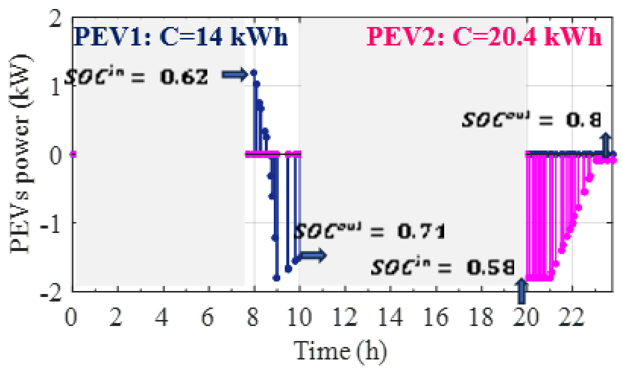
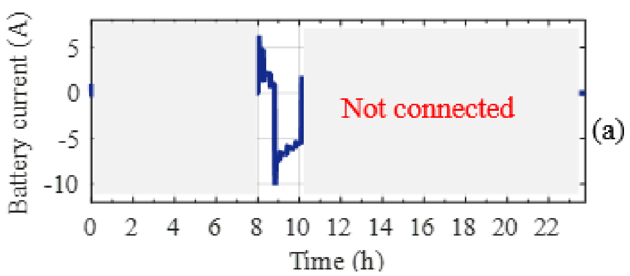


Fig. 8. Charging power profile for two PEVs in CS2.

Moreover, the charging characteristic of these two typical PEVs are shown in the following graphs. Indeed, Fig.9 and Fig.10 display the evolution of battery current and dynamic battery voltage of these two PEVs.



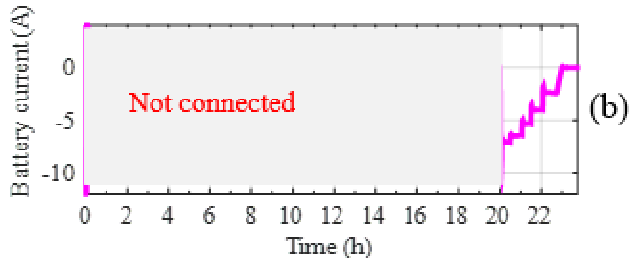


Fig.9. Current profile of PEVs battery: (a) PEV1, (b)PEV2

The current profile of two PEVs battery serves as confirmation for the adopted convention denoting positive PEVs currents correspond to discharging action, whereas negative PEVs currents correspond to charging action. As evident from **Fig.10**, the dynamic PEV voltage reveals that in the G2V paradigm, the voltage of these considered PEVs increases, while in the V2G paradigm, it decreases. Additionally, the voltage remains steady at both lower and upper SOC rates. To confirm the suggested control strategy effectiveness and each studied CS stability regarding PEVs power transactions balance,

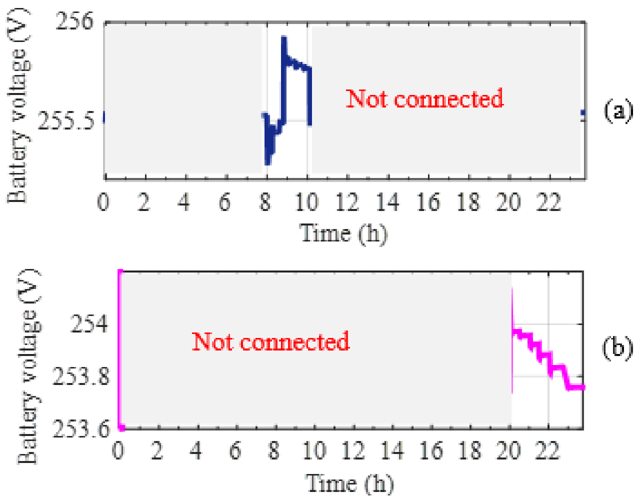


Fig. 10. Voltage profile of PEVs battery: (a) PEV1, (b)PEV2

Fig.11 investigates the modulated currents "$I_{m\text{-}bat}$" and "$I_{m\text{-}inv}$" of these PEVs in the appropriate CS2. In particular, the modulated currents exhibit a remarkable level of similarity confirming the efficacy of the control strategy. Based on the CS power management algorithm elaborated in this investigation, Fig.12 illustrates the reorganization among four distinct modes characterizing the adjustment of load power for the three studied CSs. Remarkably, for every CS, mode 1 signifies that the CS conventional power is already in improved situation. Mode 2 denotes an absence of control either from the PEVs contribution of the identifiable CS or from the PEVs of neighboring CSs, resulting in an unaltered load power curve.

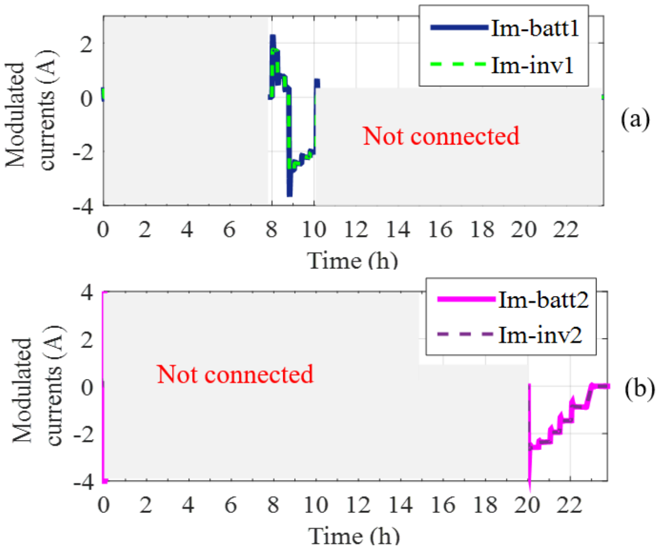


Fig. 11. Modulated currents profile of PEVs: (a) PEV1, (b)PEV2.

Mode 3 depicts a local control scenario wherein the enhancement of each CS's conventional load is made possible thanks to the effective contribution of the own PEVs performing therefore the LSC power arrangement. Mode 4 proves a central power control wherein the power demand is smoothed out as a result of PEVs contributions from neighboring CSs performing the CSC power collaboration and succeeding G2V and V2G technologies.

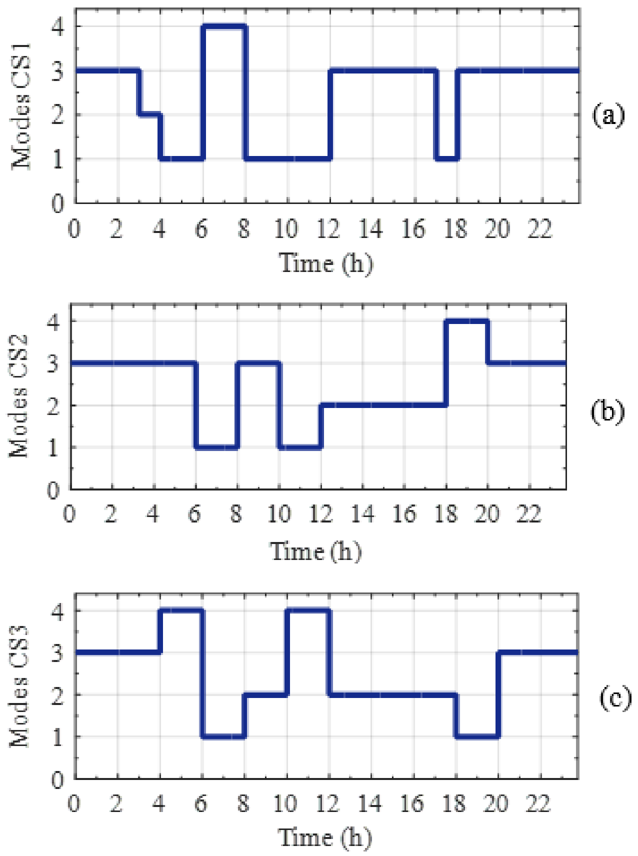


Fig. 12. Selective modes for each CSi: (a)CS1, (b)CS2, (c)CS3.

Fig.13 gives a comprehensive visualization comparing the power demand for each studied CS across three distinct stages. In the initial stage, represented by the blue curve, the conventional load power is depicted without any regulation in place showcasing valleys and peaks within the profile. It's discernible that the incorporation of scheduled PEVs power tailored for each CS effectively mitigates high power peaks and helps fill the troughs. This corresponds to the reference power with LSC. Furthermore, the implementation of CSC involves the contribution of PEVs from neighboring CSs. This contributes to a noteworthy enhancement of the load profile, resulting in a smoothed curve. The approach effectively accomplishes the goals of filling valleys and shaving peaks for all studied CSs conventional load, as depicted by the red curve.

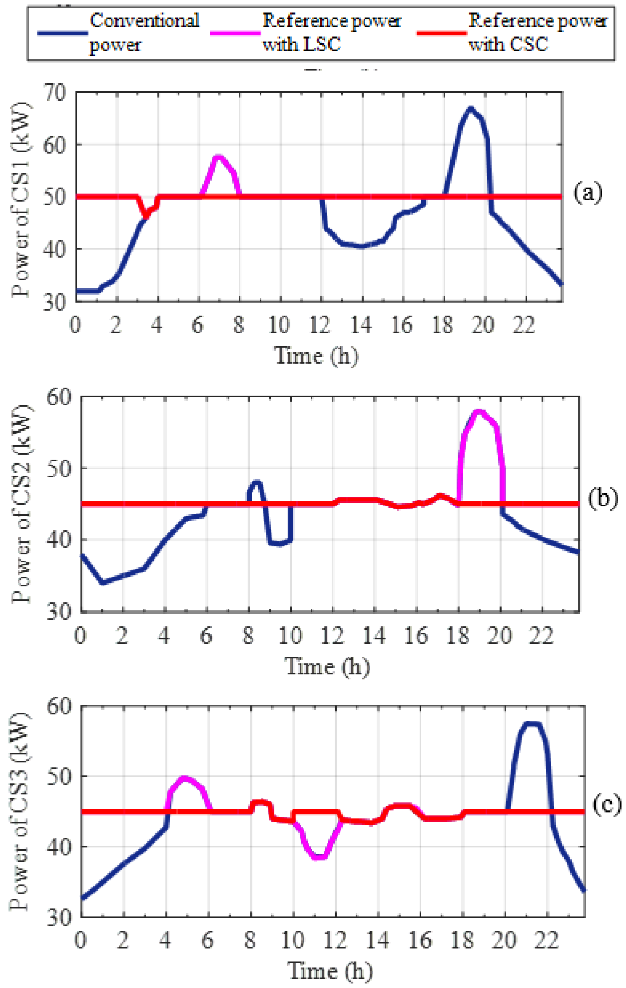


Fig. 13. Power comparison of each studied CSi: (a)CS1, (b)CS2, (c)CS3

Indeed, Table 2 provides a brief comparison to demonstrate the effectiveness of the proposed charging station energy supervision strategy.

It is worth noting that our proposed charging station energy supervision strategy has significantly flattened the load fluctuations in these studied CSs equipped with bidirectional PEVs power flow. Notably, peak demand is reduced with LSC and further decreased with CSC.Additionally, valley filling is initially achieved with

LSC and further improved with CSC performing the G2V process.

The improvement is particularly evident when comparing the results of our proposed approach with [11, 23], where the total load power is regulated by using one or two PEVs with flexible grid connection times. It is evident that in [11, 23], the peak load power exhibits a significant reduction with the innovative V2G technology, but during such time intervals the load curve may not be optimally smoothed due to limitations such as when the PEV is unable to provide or store power immediately (either because it has reached its minimum or maximum battery SOC value) or when no PEVs are connected to the smart grid. It's important to highlight that the methods mentioned above contribute to improving load power, while our strategy achieves the overall power profile's smoothness through the integration of a large number of PEVs in the respective CS and the cooperation of PEVs neighbors, achieved by both LSC and CSC.

Table 2. Comparison of valley demand and peak load values for each studied CS under LSC and CSC.

CSs	Load value of Valley filling			Load value of Peak shaving		
	original value (kW)	After LSC (kW)	After CSC (kW)	original value (kW)	After LSC (kW)	After CSC (kW)
CS 1	32	46	46	67	57	50
CS 2	34	45	45	58	58	46.2
CS 3	32.6	38.4	43.5	57.5	49.8	45.9

Fig.14 yields the cumulative load of the three studied CSs. Notably, the total load curve displays its improvement through the PEVs self-control of LSC and attains further a smoothed-out profile through the power control of neighboring CSs performing the CSC.

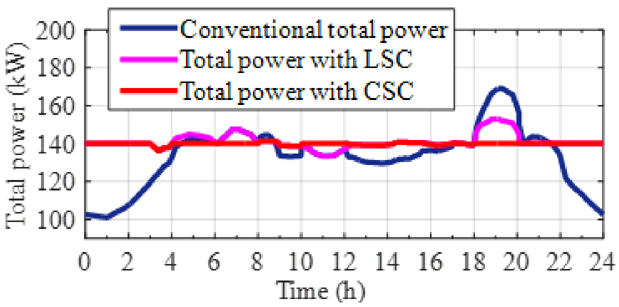


Fig. 14. Total power demand evolution for all three CSs.

5. Conclusion

The study in this paper carries out the optimal PEVs power management for three CSs showing their harmonious energy coordination with the electrical grid. Local and central supervision centers were investigated by elaborating an effective approach to cooperatively control each CS conventional load profile. This approach takes into account several constraints, including the base CS load, the demand of its neighboring CSs, the PEV arrival and departure moment from the respective CS, the availability of PEVs' neighbors, their initial battery SOC as well as the upper and lower PEVs battery limits. The objective is to effectively manage the power distribution of PEVs within their respective CS locations, coordinate the bidirectional power exchange of PEVs between neighboring CSs and correlate therefore demand with supply. The main contribution of this research is the fulfilment of the conventional power smoothness for each studied CS under four distinctive operating modes. Compared to existing methods in the field, this proposed supervision strategy ensures a notable reduction in peak intensity through the application of LSC. Besides, it achieves a more significant peak load shaving through the collaborative involvement of PEVs from neighboring CSs, thereby efficiently implementing the CSC. The energy management strategy extends to PEV battery control to optimally preserve battery lifespan and robustness. Furthermore, a little comparison of the valley and the peak values for the studied CSs loads was carried out to reveal the effectiveness of the proposed approach. These outcomes highlight their ability to decrease fluctuations in the base demand of each CS, leading to its smoother curve and accordingly reducing the stress on the current smart grid infrastructure. In future endeavours, we will shift our focus towards the PEVs charging/discharging impacts on their battery's life cycle, performance and overall lifetime. Additionally, we may consider incorporating the PEVs degradation cost modelling as one of the limiting dynamics for energy storage systems. Likewise, the investment cost associated with the practical implementation of this proposed supervision strategy and its payback period, might also be explored in future works.

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