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Optimal Utilization of Charging Resources of Fast Charging Station with Opportunistic Electric Vehicle Users

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Abstract: The key challenge with the rapid proliferation of electric vehicles (EVs) is to optimally manage the available energy charging resources at EV fast-charging stations (FCSs). Furthermore, the rapid deployment of fast-charging stations provides a viable solution to the potential driving range anxiety and charging autonomy. Costly grid reinforcements due to extra load caused by fast charging can be omitted using a dedicated energy storage and/or renewable energy system at the FCS. The energy supply and fixed number of EV supply equipment (EVSE) are considered as the limited charging resources of FCS. Amidst various uncertainties associated with the EV charging process, how to optimally utilize limited charging resources with opportunistic ultra-fast charging EV users (UEVs) is studied in this work. This work proposes resource allocation and charging coordination strategies that facilitate UEVs to dynamically exploit these limited charging resources with defined liabilities when pre-scheduled users (SEVs) do not occupy them to utilize limited charging resources maximally. Moreover, the proposed dynamic charging coordination strategies are analyzed with a Monte Carlo simulation (MCS). The presented numerical results reveal that the major drawbacks of under-utilization of limited charging resources by SEVs can be significantly improved through dynamic charging resource allocation and coordination along with UEVs. With the proposed charging coordination strategies in this study, the maximum charging resource utilization of considered FCS with 10 EVSE has been improved to 90%, which bounds to 78% only with SEVs.

Keywords: electric vehicles; DC fast charging; fast-charging station ; performance assessment of EV charging; hierarchical charging control

Citation: Konara, K.M.S.Y.; Kolhe, M.L.; Ulltveit-Moe, N.; Balapuwaduge, I.A.M. Optimal Utilization of Charging Resources of Fast Charging Station with Opportunistic Electric Vehicle Users. *Batteries* **2023**, *9*, 140. https://doi.org/10.3390/batteries9020140

Academic Editor: Jinhao Meng, Xiaoyu Li, Xu Liu

Received: 14 December 2022
Revised: 4 February 2023
Accepted: 13 February 2023
Published: 19 February 2023

1. Introduction

The proliferation of electric vehicles (EVs) does have enough potential to significantly reduce environmental and health-related issues caused by vehicular contaminant emissions. The rapid adoption of EVs on roads contributes to the United Nations' sustainable development goals (SDGs) in terms of mobility to achieve an affordable, reliable, and sustainable mode of transportation [1]. Electric transportation provides feasible solutions to the high reliance on fossil fuels and the volatility of their prices, in addition to environmental and health concerns associated with fossil-fuel based transportation [2].

The required number of EVs on the road needed to accomplish net-zero emission targets defined by the International Energy Agency (IEA) remain enormous, as the current EV market share is significantly lower than what is required [3,4]. In this context, high vehicle cost, long charging time, range anxiety, and charging autonomy pose major challenges to promoting EVs. Although high EV battery capacity assures a high driving range, it increases weight as well as represents a high share of EV price [5,6]. Moreover, currently, EV batteries are emerging with high energy and power densities in addition to long-life time due to perceptible advancements in lithium-ion battery technology over the last decade. Therefore, high energy and power-dense batteries and modern energy conversion technologies enable EV manufacturers to produce high-capacity EVs with fast charging capabilities [7–10].

Currently, EV and/or EV supply equipment (EVSE) manufacturers produce DC off-board chargers that can potentially provide high power ratings ranging from 50 kW to 400 kW [11]. Therefore, DC fast-charging stations (FCSs) can be deployed widely to overcome the challenges that are barriers to promoting EVs. Sparsely deployed FCSs may promote wholesale market adoption of lightweight EVs, as they can have similar refueling experience to gasoline counterparts [12].

Although the sparse deployment of FCSs would alleviate charging and range concerns of long trips without requiring costly high-capacity EVs, high penetration of FCSs poses substantial impacts on the power grid in terms of network capacity, power system stability, and power quality. When FCS demand grows, rapid voltage changes and voltage flicker take place at the distribution grid. An FCS is a significant harmonic emission source to the grid that results in both voltage and current harmonic distortion. As EVSE are power electronic-based systems, an FCS causes super harmonic distortion in the power grid [13]. Therefore, increasing penetration of FCSs into the distribution grid requires costly grid reinforcements or reconstructions to avoid issues related to power quality, network capacity, and energy market operation [13,14]. However, these costly grid reinforcements and reconstructions can be mitigated by embedding a renewable energy system (RES) or energy storage (ES) into the FCS while employing a coordinated charging scheme [15–17]. Therefore, the contract demand, RES, or ES can be considered as the energy supply of the FCS that should ensures uninterruptible supply. To avoid grid stresses, the power supply of the FCS should strictly adhere to grid constraints while maximally utilizing the local energy supply.

Usually battery technology limits the maximum charging power. The material used for the battery electrodes affects the energy and power density of a lithium-ion battery. Moreover, the maximum charging power of a battery depends on the thermal performance of the cell, and the cooling arrangement in both the cell and pack level has a great impact on a battery's maximum charging power [18–21]. The majority of commercial EV models are equipped with battery packs with a size ranging from 10 kWh to 100 kWh, along with specific charging constraints. Therefore, this wide range of charging demand has to be taken into consideration when developing charging coordination and scheduling schemes. To cope with the wide range of charging demand, the ICE61851 [22] and ICE62196 [23] standards contemplate a wide range of DC-fast chargers capable of providing fast and ultra-fast charging.

As far as commercially available EV models are concerned, it takes several minutes to a few hours for rechargem depending on the EV capacity, charging constraints of the EV batteries, the current state of charge (SoC), and EV user preferences. Therefore, it necessitates a charging scheduling scheme specially for time-consuming charging processes to optimize the charging process while adhering to a set of constraints enforced by the power grid and energy market. Different objectives related to the EV charging process at the FCS can be considered to formulate the optimization problem for EV charging. In this context, extensive research studies have been devoted to schedule EVs and coordinate the charging process at a CS over a planning horizon by considering various objectives such as economic aspects, operational aspects, service quality aspects, etc. Those research efforts focused on managing the EV fleet at FCSs can be basically split into two categories: (1) off-line or online/time-advance or real-time strategies; (2) static or mobility-aware strategies. Furthermore, most of the charging scheduling schemes presented in the literature employ a hierarchical architecture that allows tackling different objectives/aspects at different hierarchical layers [24]. Most of the presented deterministic charging scheduling optimization problems assume that the input data for the problem are accurately known in advance [24–26].

Although an offline strategy obtains the optimum charging schedule, due to various uncertainties associated with EV charging, illustrated in Figure 1, the expected revenue might not be accomplished in real-time operation, and the obtained solution would not be a feasible or practical one. In order to cope with these uncertainties, authors have incorporated several techniques to optimally schedule EVs at the CS with this hierarchical approach. In some cases (e.g., [27,28]), intermediate or upper layers schedule charging processes with a static approach as an offline schedule, and the CS execute this schedule in real-time using a straight-forward heuristic algorithm with less computational overhead to cope with the dynamic environment.

In some other set of studies presented (e.g., [29,30]), the proposed static algorithm is executed iteratively to deal with the stochastic nature of the EV charging process. To minimize the revenue loss due to cancellations of scheduled charging processes and unexpected departures, authors in [31] proposed multi-aggregator collaborative scheduling. As the EV demand can be shared among multiple aggregators in these strategies, the peak load caused by the high penetration of EVs can be smoothed at the power grid level.

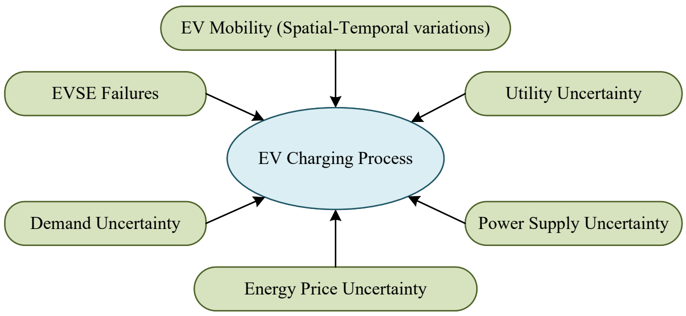

Figure 1. Uncertain aspects for EV charging process [24].

This research focuses more on the benefits of the CS (aggregator) rather than the distinct charging demands of heterogeneous EV users. In these studies, attention was given to admitted EVs at the CS. Research into charging management of plugged-in EVs can be useful from the aggregator and grid stability perspectives, but to counterbalance customer/EV user satisfaction, it is important to consider the quality of service related to EV charging in terms of EV blockage, preemptage, reliability, availability, etc. More importantly, optimal utilization of the FCS capacity with limited energy resources is an open research hotshot. Nevertheless, the proposed strategies would have been more realistic, feasible, and practical if a limited number of chargers/EVSE had been considered in the aforementioned research.

These research studies [32,33] proposed their charging scheduling strategies by considering limited charging resources. However, they have employed only the charging station capacity in their analysis but not the limited number of chargers/ EVSE. In a more realistic charging coordination scheme, the number of chargers/ EVSE and their individual capacity put another constraint on the charging coordination. However, limited charging resources including both energy resources and chargers/EVSE might not be optimally utilized by the registered/scheduled EV users due to various uncertainties, shown in Figure 1, in dynamic conditions. Moreover, scheduling the charging processes with only a few minutes of duration (long-trip drivers or ultra-fast charging users) might not be realistic. Although substantial research efforts have been devoted to optimal scheduling of EVs at a CS, how to effectively exploit unused limited charging resources allocated for scheduled users (SEVs) to further enhance resource utilization is not adequately analyzed to the best of the authors' knowledge.

Therefore, we propose event-based dynamic charging resource allocation and charging coordination strategies so that opportunistic ultra-fast charging users (UEVs) are allowed with different access privileges to exploit unused limited charging resources when registered SEVs are not very active within the FCS. In this work, we employ Monte Carlo simulation approach to assess the performance of the FCS in terms of charging resource utilization, charging completion, and quality of service aspects.

The novel technical contributions from this work can be summarized as follows:

1. Dynamic charging resource coordination strategies are proposed so that UEVs can exploit unused limited charging resources to enhance the charging resource utilization at the FCS while assuring high-quality service for both types of users.
2. Resource allocation and charging coordination is performed in a manner that the system changes its state when an event occurs and it remains until the next event occurs. This alleviates more practical issues of frequent on–off or modulating charging coordination strategies.
3. Performance evaluation parameters are defined and analyzed in a generic nature to evaluate the quality of service (QoS) of charging processes of SEVs and UEVs.

The subsequent sections of this paper are organized as follows. Section 2 describes the proposed dynamic charging resource coordination strategies. In Section 3, Monte Carlo simulation-based performance assessment framework associated with proposed charging coordination strategies is elaborated in Section 3.2, followed by Section 3.3 that explains the FCS centric performance assessment framework. Section 4 discusses obtained results from the developed MCS for selected scenarios. Finally, Section 5 concludes the innovative findings while highlighting further work related to this effort.

2. Dynamic Charging Coordination Strategies

An FCS is built with a limited number of off-board chargers/EVSE and energy supply units with limited capacity. Therefore, a commercial FCS intends to maximize the profit by scheduling EVs optimally with the effective use of available limited resources. However, due to various uncertainties associated with the scheduled charging process, charging resources may not be optimally utilized even though the EV schedule obtains the maximized profit with SEVs. In order to get the advantage of very short charging time associated with ultra-fast charging technology, this work intends to evaluate the overall performance of an FCS that serves both SEVs and opportunistic ultra-fast charging EV users (UEVs), as illustrated in Figure 2.

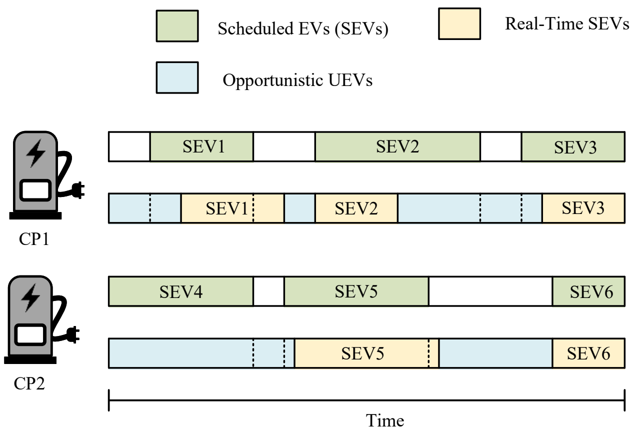

Figure 2. Utilization of charging resources by UEVs.

When we consider the operation of FCS, there are basically two types of EV users, as tabulated in Table 1: (1) SEVs and (2) UEVs with distinct privileges and constraints in accessing the FCS.

Table 1. Access privileges and constraints of EV users.

SEVs	**UEVs**
• Access according to a prior agreement	• Access opportunistically
• Charged at specified charge rate $P_s;\ P_s \in\ [P_s^{min}, P_s^{max}]$	• Charged at specified higher charge rate $P_u = nP_s; (n \in\ \mathbb{Z}^+)\ , P_u \in [P_u^{min}, P_u^{max}]$
• Charger is guaranteed during scheduled time	• Charger is assigned if charging resources are available only
• Not subject to blockages	• Subject to blockages
• Charging process regularly finishes	• Charging process is liable to be preempted before regularly finishes
• Expect uninterruptible EV charging	• Expect to charge as quickly as possible

The prime objective of FCS is to provide uninterruptible EV charging to SEVs who have prior agreements with the FCS. The operating model of the considered FCS is illustrated in Figure 3.

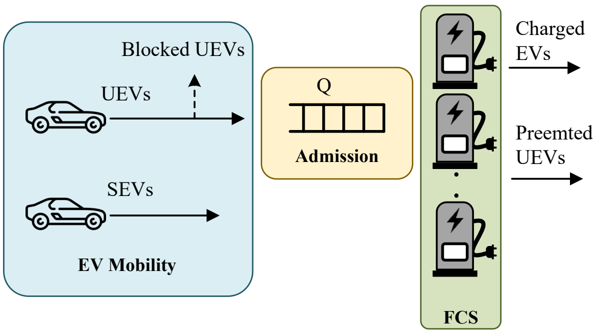

Figure 3. Proposed operation mechanism of the FCS [34–36].

In this work, we have considered an already deployed FCS with $M;\ (M \in \mathbb{Z}^+)$ number of off-board chargers (OBCs), and it is assumed that the charging power of each charger can be adjustable. A queue space (Q) with q number of queue points (QPs) is allocated so that newly arrived UEVs are queued if charging resources are not available. In the meantime, FCS admits opportunistic UEVs to compensate for under-utilization of limited charging resources. SEVs are charged at a specified charge rate of $P_s; P_s \in [P_s^{min}, P_s^{max}]$. Consequently, the capacity of FCS is limited to MP_s^{max} throughout the operating horizon. Therefore, depending on the availability of charging resources, UEVs can be charged at high charge rate. Based on the day-to-day life activities of EV users and the charging constraints of EV batteries, some EV users may need undisturbed and prioritized EV charging (i.e., SEVs). At the same time, some other EV users just want to enhance their cruise range by refilling their high-capacity EV batteries up to the maximum possible level quickly during their journey. Consequently, they can be considered as UEVs. Therefore, FCSs should have a charging pricing mechanism for SEVs and OEVs based on charging priorities. Moreover, EVs capable of ultra-fast charging with high charging power rates can request to be an UEV so that they can charge their EVs with an economical pricing scheme. In this work, we assume that the charging rate of UEVs is nP_s and the value n is selected such that nP_s is less than the maximum capacity of an OBC (P_c^{max}). Therefore, it is considered that $P_c^{max} = nP_s^{max}$.

Although the OBC capacity is nP_s^{max}, we consider that the initial capacity of the FCS is MP_s^{max}. In this work, we intend to analyze the possibility of enhancing capacity utilization with the help of heterogeneous EV users. However, with regard to M OBCs, the maximum capacity of FCS is nMP_s^{max}. Depending on the progressing charging demand, the capacity of the FCS can be scaled up to nMP_s^{max} from MP_s^{max}.

3. Methods

This work intends to develop a Monte Carlo simulation-based performance assessment framework to analyze proposed charging resource coordination strategies.

When we consider the whole charging management at the FCS, there are two stages: (1) scheduling SEVs in a optimal way to maximize the profit; (2) admitting UEVs as secondary users to further enhance the utilization of limited charging resources. In this work, we focus on the impact of opportunistic users over SEVs and themselves. Monte Carlo simulation is used to analyze system dynamics and uncertainties associated with the EV charging process.

3.1. Stochastic EV Mobility Model

Monte Carlo simulation is developed to analyze proposed charging coordination strategies. Therefore, the following assumptions are made to develop this MCS model.

- The arrivals of SEVs and UEVs are Poisson processes with mean arrival rates of λ_s and λ_u, respectively (λ denotes the average number of charging requests made by the respective category of EVs per unit time).
- All OBCs are homogeneous and the charging time of a OBC is exponentially distributed with the service rate of μ_c (μ_c rate denotes the average number of charged EVs per OBC per unit time).
- Admission delays associated with EVs at the FCS are negligible as compared to charging times.

The EV mobility model is developed as a continuous-time discrete-space stochastic model. The arrival rate and service rate are considered as time-dependent data to cater system dynamics. Let T be the planning horizon and thus, we consider δt intervals over T. Consequently, the planning horizon can be denoted as $(0, \delta t, 2\delta t, \ldots, t, t+\delta t, t+2\delta t, \ldots, T)$. It is considered that the number of arrivals within time interval t follows a Poisson distribution under the following conditions. If the average arrival rate of EVs is λ_t ($\lambda_t > 0$) over the $[t,\ t+\delta t]$, the probability of one arrival of EV during $[t,\ t+\delta t]$ is $\lambda_t t + O(\delta t)$; $O(\delta t)$: order of δt. The probability of more than one arrival of EVs during $[t,\ t+\delta t]$ is $O(\delta t)$. The occurrence of EV arrivals in non-overlapping intervals are mutually independent. Then, the number of EV arrivals $(N_t,\ t \geq 0)$ occurring during $[t,\ \delta t]$ can be modeled as a Poisson process with parameter λ_t as expressed in (1) [34–36].

$$P\{N_t\} = \frac{\exp(\lambda_t)(\lambda_t)^{N_t}}{N_t!} \tag{1}$$

3.2. Dynamic Charging Coordination Model

To develop the MCS model with proposed event-based dynamic charging coordination strategies, the following events are considered: SEV or UEV arrivals at FCS and SEV or UEV departures from FCS. Each plugged-in EV and each queued EV are sequentially indexed and placed in dynamic arrays $\left(\boldsymbol{A}^{ev}_{j_{ev}(t)\times l};\ j_{ev}(t) \leq M\right)$ and $\left(\boldsymbol{A}^{q}_{j_q(t)\times l};\ j_q(t) \leq Q\right)$, respectively, to analyze system dynamics. Let t^a_k, t^p_k, t^c_k, t^r_k, α_k, and β_k be the arrival time, plugged-in time, required charging time, remaining charging time, EV user type, and index of the kth $(k \in\ \mathbb{Z}^+)$ plugged-in EV, an element of $\boldsymbol{A}^{ev}_{j_{ev}(t_k)}$ associated with the kth SEV or UEV arrival at time t_k can be expressed as (2). Similarly, an $\boldsymbol{A}^{ev}_{j_{ev}(\tau_m)}$ element is derived for an SEV or UEV departure at time τ_m. If t_c follows the exponential distribution, it is expressed in (3).

$$\boldsymbol{A}^{ev}_{j_{ev}(t_k)} = \left\{t^a_k,\ t^p_k,\ t^c_k,\ t^r_k,\ \alpha_k,\ \beta_k\right\} \tag{2}$$

$$P(t_c, \mu_c) = \frac{1}{\mu_c}\exp\left(\frac{-t_c}{\mu_c}\right) \tag{3}$$

The MCS model keeps its current state in terms of allocated resources, the number of plugged-in EVs, and their charging power unchanged until the next event occurs.

Information pertaining to all possible events is kept in matrix $\boldsymbol{A}^{\boldsymbol{ev}}_{\boldsymbol{M \times I \times T}}$. Therefore, $\boldsymbol{A}^{ev}$ that accounts for all possible x events taken place at $t_1, t_2, \ldots, t_x$ within 0 to T can be expressed as (4). Similarly, all the information of queued EVs at each event is kept in $\boldsymbol{A}^q$ expressed in (5).

$$\boldsymbol{A}^{ev} = \left[\boldsymbol{A}^{ev}_{j_{ev}(t_1)},\ \boldsymbol{A}^{ev}_{j_{ev}(t_2)},\ \ldots, \boldsymbol{A}^{ev}_{j_{ev}(t_k)},\ \boldsymbol{A}^{ev}_{j_{ev}(t_{k+1})},\ \ldots, \boldsymbol{A}^{ev}_{j_{ev}(t_x)}, \right] \tag{4}$$

$$\boldsymbol{A}^{q} = \left[\boldsymbol{A}^{q}_{j_q(t_1)},\ \boldsymbol{A}^{q}_{j_q(t_2)},\ \ldots, \boldsymbol{A}^{q}_{j_q(t_k)},\ \boldsymbol{A}^{q}_{j_q(t_{k+1})},\ \ldots, \boldsymbol{A}^{q}_{j_q(t_x)}, \right] \tag{5}$$

The FCS is obliged to admit SEVs if they arrive within the scheduled time period. For charging resource allocation, M number of OBCs and a queue with Q number of queuing points (QPs) $(M, Q \in \mathbb{Z}^+)$ are considered. The queue is reserved only for UEVs at the arrival if charging resources are not adequate to admit them. To update system matrix $\boldsymbol{A}^{ev}$ and $\boldsymbol{A}^q$, the following events are considered.

Arrival of SEVs at FCS: Charging resource allocation for SEVs is illustrated in Algorithm 1. When an SEV arrives at the FCS at time t_k, if there is at least one idle CP, it is plugged into the FCS without disturbing any ongoing UEV charging process. Otherwise, one charging process of UEV has to be preempted to admit the newly arrived SEV, as they are liable to do so.

Algorithm 1: Pseudo code (PC) for updating $A^{ev}_{j_{ev}(t_k)}$ at SEV arrivals.

```
Input  : j_s(t_k) : Number of plugged-in SEVs at time t_k
Input  : j_u(t_k) : Number of plugged-in UEVs at time t_k
Input  : j_sa(t_k) : Total number of arrived SEVs at time t_k
Input  : j_ev(t_k) : Total number of plugged-in EVs by time t_k
Output : A^ev_{j_ev(t_k)} : Plugged-in EVs matrix at time t_k
Output : A^q_{j_q(t_k)} : Queued EVs matrix at time t_k

if j_s(t_k) + n j_u(t_k) < M then
    j_s(t_{k+1}) = j_s(t_k) + 1,  j_u(t_{k+1}) = j_u(t_k)
    j_sa(t_{k+1}) = j_sa(t_k) + 1,  j_ev(t_{k+1}) = j_ev(t_k) + 1
    SEV is plugged-into an idle OBC.
    A^ev_{j_ev(t_{k+1})}(i; α_k ~ idle) = { t^a_{k+1}, t^p_{k+1}, t^c_{k+1}, t^r_{k+1}, α_{k+1}, β_{k+1} }
else if j_s(t_k) + n j_u(t_k) == M AND j_u(t) > 0 then
    j_s(t_{k+1}) = j_s(t_k) + 1,  j_u(t_{k+1}) = j_u(t_k) − 1
    j_sa(t_{k+1}) = j_sa(t_k) + 1,  j_ev(t_{k+1}) = j_ev(t_k)
    SEV is plugged-into the vacated OBC by UEV.
    A^ev_{j_ev(t_{k+1})}(i; α_k ~ uev) = { t^a_{k+1}, t^p_{k+1}, t^c_{k+1}, t^r_{k+1}, α_{k+1}, β_{k+1} }
else
    Block the SEV
end
```

Departure of SEVs from FCS: Algorithm 2 explains how charging resources are coordinated upon a departure of SEV at time t_k. Once an SEVs' charging process regularly finishes, it departs the FCS, resulting in an idle OBC. For this OBC, the chance is given to queued UEVs if any. Otherwise, the OBC will be idle.

Algorithm 2: PC for updating $A^{ev}_{j_{ev}(t_k)}$ and $A^{q}_{j_q(t_k)}$ at SEV departures.

Input : $j_s(t_k)$: Number of plugged-in SEVs at time t_k
Input : $j_u(t_k)$: Number of plugged-in UEVs at time t_m
Input : $j_q(t_k)$: Total number of queued UEVs at time t_k
Input : $j_{ev}(t_k)$: Total number of plugged-in EVs at time t_k
Input : $A^{q}_{j_q(t_k)}$: Queued EVs matrix at time t_k
Output: $A^{ev}_{j_{ev}(t_k)}$: Plugged-in EVs matrix at time t_k

$j_s(t_{k+1}) = j_s(t_k) - 1$
if $\left(0 < j_q(t_k) \leq Q\right)$ AND $(M - (j_s(t_{k+1}) + nj_u(t_k)) \geq n)$ **then**
  $j_u(t_{k+1}) = j_u(t_k) + 1$
  $j_q(t_{k+1}) = j_q(t_k) - 1,\ j_{ev}(t_{k+1}) = j_{ev}(t_k)$
  Queued UEV is plugged-in.
  $\boldsymbol{A}^{\boldsymbol{ev}}_{\boldsymbol{j_{ev}(t_{k+1})}}(i; t^r_k == 0) = \boldsymbol{A}^{\boldsymbol{q}}_{\boldsymbol{j_q(t_k)}}(1)$
else
  $j_s(t_{k+1}) = j_s(t_k) - 1,\ j_u(t_{k+1}) = j_u(t_k)$
  $j_q(t_{k+1}) = j_q(t_k),\ j_{ev}(t_{k+1}) = j_{ev}(t_k) - 1$
  OBC is idle.
  $\boldsymbol{A}^{\boldsymbol{ev}}_{\boldsymbol{j_{ev}(t_{k+1})}}(i; t^r_k == 0) = \mathbf{0}$
end

Arrival of UEVs at FCS: The FCS accepts UEVs if SEVs do not occupy all the OBCs. The charging process of plugged-in UEVs are not preempted upon the arrival of a new UEV. When a new UEV arrives at the FCS, it is plugged in if at least an OBC and enough energy resources are available to provide a charge rate of P_u^{max}. Otherwise, the UEV is blocked. Charging resource allocation for newly arrived UEVs is illustrated in Algorithm 3.

Algorithm 3: PC for updating $A^{ev}_{j_{ev}(t_k)}$ and $A^{q}_{j_q(t_k)}$ at UEV arrivals.

Input : $j_s(t_k)$: Number of plugged-in SEVs at time t_k
Input : $j_u(t_k)$: Number of plugged-in UEVs at time t_k
Input : $j_{ua}(t_k)$: Total number of arrived SEVs at time t_k
Input : $j_{ev}(t_k)$: Total number of plugged-in EVs by time t_k
Output: $A^{ev}_{j_{ev}(t_k)}$: Plugged-in EVs matrix at time t_k
Output: $A^{q}_{j_q(t_k)}$: Queued EVs matrix at time t_k

if $M - (j_s(t_k) + nj_u(t_k)) \geq n$ **then**
  $j_s(t_{k+1}) = j_s(t_k),\ j_u(t_{k+1}) = j_u(t_k) + 1$
  $j_{ua}(t_{k+1}) = j_{ua}(t_k) + 1,\ j_{ev}(t_{k+1}) = j_{ev}(t_k) + 1$
  UEV is plugged-into an idle OBC.
  $\boldsymbol{A}^{\boldsymbol{ev}}_{\boldsymbol{j_{ev}(t_{k+1})}}(i; \alpha_k \sim idle) = \left\{t^a_{k+1},\ t^p_{k+1},\ t^c_{k+1},\ t^r_{k+1},\ \alpha_{k+1},\ \beta_{k+1}\right\}$
else if $j_q(t_k) < Q$ **then**
  $j_s(t_{k+1}) = j_s(t_k),\ j_u(t_{k+1}) = j_u(t_k) + 1$
  $j_{sa}(t_{k+1}) = j_{sa}(t_k) + 1,\ j_{ev}(t_{k+1}) = j_{ev}(t_k)$
  UEV is queued.
  $\boldsymbol{A}^{\boldsymbol{q}}_{\boldsymbol{j_q(t_{k+1})}}(i; \alpha_k \sim vacant) = \left\{t^a_{k+1},\ t^p_{k+1},\ t^c_{k+1},\ t^r_{k+1},\ \alpha_{k+1},\ \beta_{k+1}\right\}$
else
  Block the SEV
end

Departure of UEVs from FCS: Unlike for SEVs, an UEV departure leaves one OBC and energy resources associated with n OBCs. The idle OBC(s) that appeared in the FCS due to the departure of a UEV will be offered to EVs waiting in the queue. If the queue is empty, then the vacant BCS(s) become idle. The charging resource coordination upon a UEV departure is performed according to Algorithm 4.

Algorithm 4: PC for updating $A^{ev}_{j_{ev}(t_k)}$ and $A^{q}_{j_q(t_k)}$ at UEV departures.

Input : $j_s(t_k)$: Number of plugged-in SEVs at time t_k
Input : $j_u(t_k)$: Number of plugged-in UEVs at time t_k
Input : $j_q(t_k)$: Total number of queued UEVs at time t_k
Input : $j_{ev}(t_k)$: Total number of plugged-in EVs at time t_k
Input : $A^{q}_{j_q(t_k)}$: Queued EVs matrix at time t_k
Output: $A^{ev}_{j_{ev}(t_k)}$: Plugged-in EVs matrix at time t_k

if $\left(0 < j_q(t_k) \leq Q\right)$ **then**
  $j_s(t_{k+1}) = j_s(t_k),\ j_u(t_{k+1}) = j_u(t_k)$
  $j_q(t_{k+1}) = j_q(t_k) - 1,\ j_{ev}(t_{k+1}) = j_{ev}(t_k)$
  Queued UEV is plugged-in.
  $\boldsymbol{A}^{\boldsymbol{ev}}_{\boldsymbol{j_{ev}(t_{k+1})}}(i; t^r_k == 0) = \boldsymbol{A}^{\boldsymbol{q}}_{\boldsymbol{j_q(t_k)}}(1)$
else
  $j_s(t_{k+1}) = j_s(t_k),\ j_u(t_{k+1}) = j_u(t_k) - 1$
  $j_q(t_{k+1}) = j_q(t_k),\ j_{ev}(t_{k+1}) = j_{ev}(t_k) - 1$
  OBC is idle.
  $\boldsymbol{A}^{\boldsymbol{ev}}_{\boldsymbol{j_{ev}(t_{k+1})}}(i; t^r_k == 0) = \boldsymbol{0}$
end

3.3. FCS Centric Performance Evaluation Parameters

At an FCS, the optimum resource allocation for EVs is very indispensable for sustainable operation. When there are two EV categories, it is necessary to analyze the blockages and waiting of inferior users.

However, high charging resource utilization may affect the charging completion rates of both plugged-in SEVs and UEVs. Upon the arrival of SEVs, some charging processes of UEVs might be preempted. Analyzing all these aspects is very essential for the FCS to provide high-quality service to EV users. In this work, we develop an MCS model with proposed resource allocation and charging coordination strategies as an event-driven model and simulate for a large time horizon until the model comes to its equilibrium. From the system matrices $(\boldsymbol{A}^{\boldsymbol{ev}},\ \boldsymbol{A}^{\boldsymbol{q}})$, we have analyzed the performance of developed strategies in terms of charging resource utilization and charging service quality.

3.3.1. Blocking Probability of UEVs $(P_{b,uev})$

Although the FCS accepts UEVs to enhance the utilization of limited charging resources, there may be occasions where a charging request from a UEV has to be dropped due to limited or unavailable charging resources. Therefore, upon arrival of a UEV at the FCS, there is a probability that the charging request is denied. This EV blockage is a crucial factor to be analyzed from a service quality perspective. A charging request from an UEV is denied when the following conditions are met at the same time: (1) all OBCs are occupied; (2) energy resources are not adequate to admit the new UEV; (3) the allocated space for the queue is full. The blocking probability of UEVs can be obtained with (6).

$$P_{b,uev} = \frac{j_{ua}(t_x) - \sum_{k=1,\ j_u(t_k) > j_u(t_{k-1})}^{x} [j_u(t_k) - j_u(t_{k-1})]}{j_{ua}(t_x)} \quad ; \ \forall \boldsymbol{A}^{ev}_{j_{ev}(t_k)|t \in [0\ T]} \tag{6}$$

3.3.2. Preempting Probability of UEVs ($P_{p,uev}$)

According to the defined admission control and charging coordination strategies, the charging process of UEVs are liable to be preempted if charging resources are not adequate to admit SEVs. This action is defined as the preempting of UEVs. Therefore, the probability at which an ongoing charging process of a UEV is forcibly terminated before being regularly finished is termed as the preempting probability of UEVs. If there are limitations for certain user types to utilize limited charging resources, the charging quality of such users is a crucial factor to be analyzed for long-term benefits. By considering derived system matrix ($\boldsymbol{A}^{ev}$), $P_{p,uev}$ can be derived as expressed in (7).

$$P_{p,uev} = \frac{\sum_{\substack{k=1, \\ j_s(t_k)>j_s(t_{k-1}),\ j_u(t_k)<j_u(t_{k-1})}}^{x} [j_u(t_{k-1}) - j_u(t_k)]}{\sum_{\substack{k=1, \\ j_u(t_k)>j_u(t_{k-1})}}^{x} [j_u(t_k) - j_u(t_{k-1})]} \quad ; \ \forall \boldsymbol{A}^{ev}_{j_{ev}(t_k)|t\in[0\ T]} \tag{7}$$

3.3.3. Mean Charging Time at the FCS ($\bar{t}_c$)

Amidst busy schedules, users prefer to get their EVs recharged as fast as possible, hence, the total time spent at the FCS is going to be a crucial measure for evaluating the service quality provided by the FCS. Total time of charging is not only essential for operation management but also for finding the optimum location and the size of the FCS within a certain area/region. Specifically, analyzing the mean time spent by an opportunistic UEV at the FCS is indispensable for assuring quality service for secondary users. The total time spent by SEVs at FCS is nothing but the required charging time to attain the requested SoC. However, as some of UEVs have to wait at the queue and terminate their charging process forcibly before being regularly finished, this $\bar{t}_c$ provides very essential QoS measurement for opportunistic users. Mean charging time of SEVs can be obtained from ($\boldsymbol{A}^{ev}$) as expressed in (8).

$$\bar{t}_{c,sev} = \frac{\sum_{\substack{k=1, \\ \beta_k \neq \beta_{k-1},\ \alpha_i \sim sev}}^{x} \sum_{i=1,}^{j_{ev}(t_k)} t_i^c}{\sum_{\substack{k=1, \\ j_u(t_k)==j_u(t_{k-1}),\ j_s(t_k)<j_s(t_{k-1})}}^{x} [j_s(t_{k-1}) - j_s(t_k)]} \quad ; \ \forall \boldsymbol{A}^{ev}_{j_{ev}(t_k)|t\in[0\ T]} \tag{8}$$

$$\bar{t}_{c,uev} = \frac{\sum_{\substack{k=1, \\ \beta_k \neq \beta_{k-1},\ \alpha_i \sim uev,\ t_i^r==0}}^{x} \sum_{i=1,}^{j_{ev}(t_k)} t_i^c}{\sum_{\substack{k=1, \\ j_s(t_k)==j_s(t_{k-1}),\ j_u(t_k)<j_u(t_{k-1})}}^{x} [j_u(t_{k-1}) - j_u(t_k)]} \quad ; \ \forall \boldsymbol{A}^{ev}_{j_{ev}(t_k)|t\in[0\ T]} \tag{9}$$

In order to analyze the total time spent by UEVs at the FCS, we consider both mean charging time ($\bar{t}_c$) and mean waiting time ($\bar{t}_q$) at the queue. Therefore, the total waiting time of UEVs over total queued UEVs gives the mean waiting time of UEVs ($\bar{t}_{q,uev}$) as expressed in (10).

$$\bar{t}_{q,uev} = \frac{\sum_{\substack{k=1, \\ \beta_k \neq \beta_{k-1},\ \alpha_i \sim uev}}^{x} \sum_{i=1,}^{j_{ev}(t_k)} t_i^a - t_i^p \quad ; \ \forall \boldsymbol{A}^{ev}_{j_{ev}(t_k)|t\in[0\ T]}}{\sum_{\substack{k=1, \\ j_u(t_k)>j_u(t_{k-1})}}^{x} [j_u(t_k) - j_u(t_{k-1})] \quad ; \ \forall \boldsymbol{A}^{q}_{j_q(t_k)|t\in[0\ T]}} \tag{10}$$

The total mean time spent by an EV user type (SEV or UEV) can be found by calculating the summation of ($\bar{t}_c$) and ($\bar{t}_q$).

3.3.4. Mean Charging Completion Rate ($\dot{c}$)

Mean charging completion rate ($\dot{c}$) of a particular EV user type implies the corresponding number of charging processes that finish regularly attaining the requested SoC within unit time. As we have employed secondary users over scheduled or registered users in the proposed strategies, it is very essential to evaluate the impact on one another in the charging process. Therefore, $\dot{c}_{sev}$ and $\dot{c}_{uev}$ are expressed in (11) and (12), respectively.

$$\dot{c}_{sev} = \frac{\sum_{k=2,}^{x}[j_s(t_{k-1}) - j_s(t_k)]/T}{j_u(t_k) == j_u(t_{k-1}),\ j_s(t_k) < j_s(t_{k-1})};\ \forall \boldsymbol{A}^{ev}_{j_{ev}(t_k)|t \in [0\ T]} \quad (11)$$

$$\dot{c}_{uev} = \frac{\sum_{k=2,}^{x}[j_u(t_{k-1}) - j_u(t_k)]/T}{j_s(t_k) == j_s(t_{k-1}),\ j_u(t_k) < j_u(t_{k-1})};\ \forall \boldsymbol{A}^{ev}_{j_{ev}(t_k)|t \in [0\ T]} \quad (12)$$

3.3.5. Charging Resource Utilization of the FCS (U)

The main objective of this work is to further maximize the utilization of limited charging resources with opportunistic UEVs providing a compensation to under-utilization of limited charging resources due to various uncertainties associated with EV charging process. Therefore, charging resource utilization is an important parameter to present the overall performance of the FCSs' operation. In this work, as we have considered the total capacity of the FCS along with the number of OBCs instead of employing a separate demand limit. The charging resource utilization (U) is defined as the steady state value of utilized OBCs over the total number of OBCs. Therefore, U can be expressed as in (13).

$$U = \sum_{k=1}^{x}[j_s(t_k) + n j_u(t_k)]/Mx;\ \forall \boldsymbol{A}^{ev}_{j_{ev}(t_k)|t \in [0\ T]} \quad (13)$$

The presented MCS based analytical model assesses the performance of proposed dynamic charging resource coordination strategies for selected categories of EV users depending on their charging priorities.

4. Results and Discussion

How to compensate under-utilization of limited charging resources of an FCS due to uncertainties associated with the SEV charging process is analyzed in this work. This section elaborates on the behavior of FCS for a variation of EV arrivals. In this section, we have incorporated derived performance assessment parameters in Section 3.3 to evaluate the ability of developed charging resource coordination strategies in enhancing the charging resource utilization while providing a satisfactory service quality for EV users. In the considered scenario, the FCS is equipped with 10 CPs (i.e, M = 10) that can adjust the charging power within a specified range in steps. The MCS parameter n is set to 2.

4.1. Charging Resource Utilization

We intend to analyze how UEVs can enhance the utilization of limited charging resources by quickly exploiting charging resources when SEVs do not occupy them. In this analysis, we consider the variation of charging resource utilization with and without UEVs.

Therefore, we have considered three cases where λ_u is set to 18 h^{-1}, 24 h^{-1}, and 30 h^{-1} while λ_s varies from 0 to 60 h^{-1}. The variation of U against λ_s is shown in Figure 4. Figure 4 depicts that unexploited charging resources by SEVs can be effectively utilized with UEVs. It is evident that proposed strategies have improved the U with opportunistic UEVs. Limited charging resources are not optimally utilized at higher values of λ_s due to high blockages of EVs. For the considered case in Figure 4, U cannot be enhanced beyond 78%. However, by allowing opportunistic UEVs to exploit unused charging resources to attain high power charging, U has been improved up to 90%.

Figure 5 plots the variation of U against λ_s and λ_u. From Figure 5, it can be seen that U cannot be improved more than 78% with SEVs, even at high arrival rates. However, by letting UEVs exploit available charging resources when SEVs are not very active within the FCS, limited charging resources can be maximally (92%) utilized. Even for lower values of λ_s, U is significantly enhanced with opportunistic UEVs. The plots of U against λ_s and λ_u shows continuous ascent with positive slope due to high blockages of EVs and preemptions of UEVs at high arrival rates.

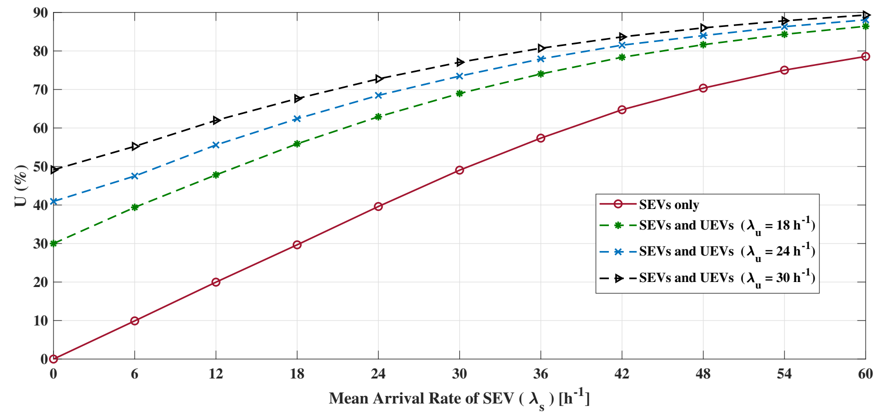

Figure 4. Charging resource utilization with λ_s.

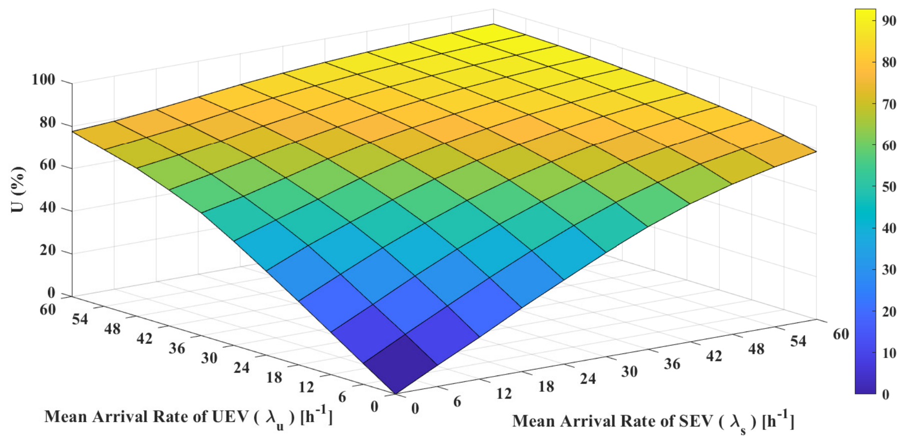

Figure 5. Charging resource utilization with λ_s and λ_u.

4.2. Mean Charging Completion Rate

To analyze the impact of opportunistic UEVs on the charging process of SEVs, the mean charging completion rate of the particular EV user type is used. The mean charging completion rate $(\dot{c})$ implies the number of completed charging processes of the considered EV user category within a unit of time. Assuring a high quality service for SEVs is dispensable as they have prior agreements for an uninterruptible charging process. Derived expressions for the mean charging completion rates of SEVs $(\dot{c}_{sev})$ and UEVs $(\dot{c}_{uev})$ (Equations (11) and (12)) are considered for the analysis in this subsection. Figure 6a,b illustrate the variation of mean completion rates of SEVs and UEVs as a function of λ_s and λ_u, respectively. The increment of SEV arrivals at the FCS deteriorates the mean charging completion rate of UEVs, but the reverse does not happen. The value of $\dot{c}_{sev}$ shows continuous ascent against λ_s with positively decreasing slope due to possible blockages of SEVs at high arrival rates. More importantly, resource coordination strategy with aggregation shows better performance in terms of the charging completion of SEVs. In order to analyze the mutual impact of EV charging completion, we have plotted $\dot{c}$ against both λ_s and λ_u within a range starting from 0 to 60 h^{-1}. As Figure 6a depicts, an increment of λ_u does not make any impact on SEVs. Nevertheless, although $\dot{c}_{uev}$ shows a continuous ascent with λ_u, the rate of change of the increment gradually decreases when λ_s is increased.

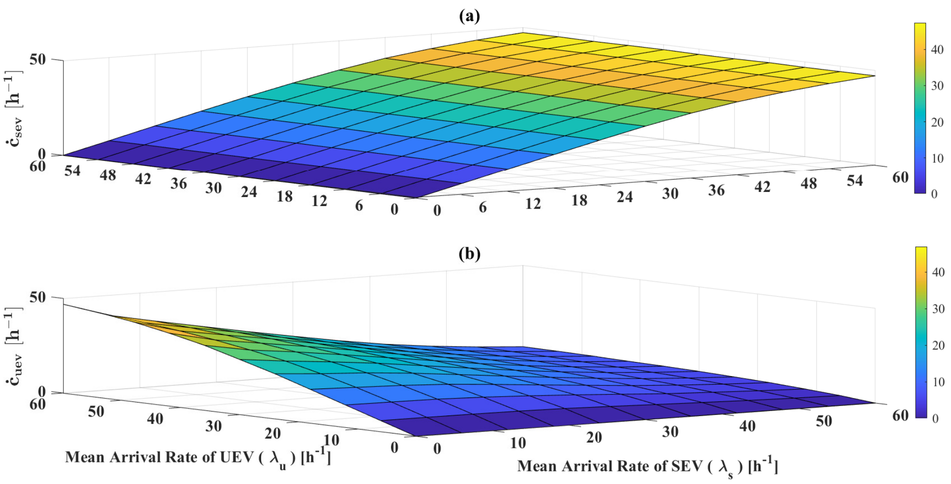

Figure 6. Mean charging completion rate of EVs with λ_s and λ_u.

4.3. Blocking and Preempting Probability of UEVs

When there are different user categories with defined privileges, assessing user satisfaction in terms of accessing and utilizing limited charging resources is vital. Especially, as UEVs are liable to have their charging process terminated forcibly if charging resources are not adequate to admit the newly arrived SEV, evaluating the likelihood of such preemptages is indispensable for long-term operation of the FCS. Therefore, we have analyzed the blocking and preempting probabilities. Figure 7a,b depict the variation of blocking and preempting probabilities of UEVs as a function of both λ_s and λ_u. From Figure 7, we can observe that both blocking and preempting probabilities of UEVs show continuous ascent with λ_s. It can be seen that the blockage and preemptage of UEVs become significant when SEVs are more active. In the considered scenario (Figure 7), for the available EV charging resources, the blocking probability gradually increases to 0.6 when λ_s increases from 0 to 60 h^{-1}.

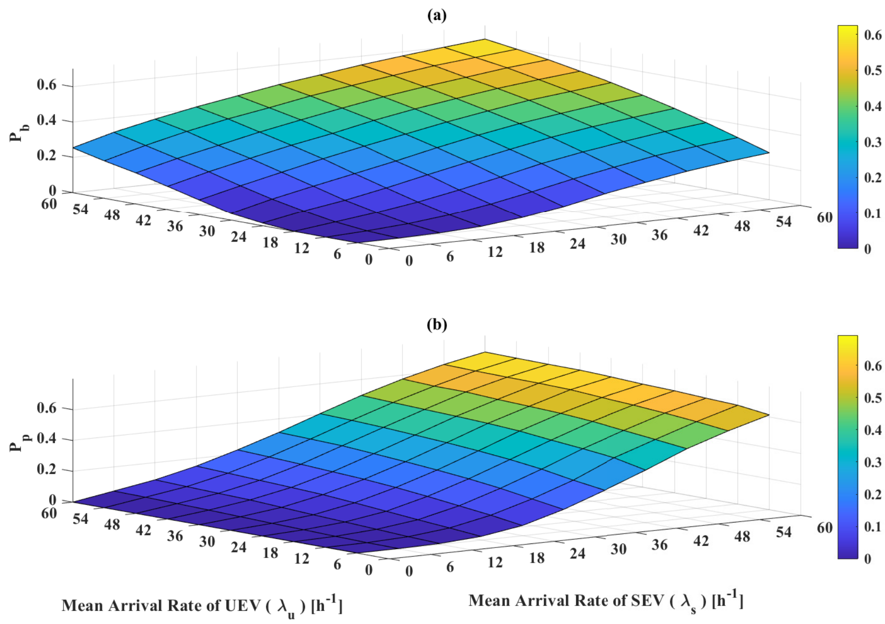

Figure 7. (**a**) Blocking and (**b**) preempting probability of UEVs with λ_s and λ_u.

Nevertheless, we can observe that blockage of UEVs is influenced by themselves. Moreover, at the same arrival rate of SEVs, preempting probability is also around 0.6, which is a bit higher value from a service quality point of view. To provide satisfactory service to UEVs, the FCS would schedule SEVs so that it does not exceed the mean arrival rate 30 h^{-1} for a considered time horizon.

All these parameters should be taken into account to evaluate the FCS centric performance.

5. Conclusions

In this paper, we have analyzed how opportunistic ultra-fast charging EV users can be incorporated to further enhance the utilization of limited charging resources. The proposed strategy enables UEVs to exploit unused charging resources by scheduled EV users at FCS to enhance charging resource utilization. Developed event-based dynamic charging resource allocation and coordination strategies are analyzed with Monte Carlo simulation. The presented results show a coordination strategy to optimally utilize the limited charging resources of FCS with opportunistic EV users considering uncertainties associated with EV charging process. In this work, the presented results prove that the developed charging resource coordination strategy significantly improves the charging resource utilization of the FCS at any arrival rate of SEVs. At higher arrival rates of EVs, FCS accomplishes more than 90% of resource utilization, which is bounded to 78% only with SEVs.

Along with the proposed strategies, we have derived a framework of a generic nature using MCS to assess the FCS-centric performance in terms of charging resource utilization, charging completion rates of EV users, blocking probability, preempting probability, waiting time, charging time, etc. This FCS-centric performance assessment framework can be incorporated at the planing and deployment stages to find the optimum siting and sizing of FCSs. At the operating stage of an FCS, the developed framework can be used to ensure a high-quality service to both SEVs and UEVs, as it provides a quantitative overview of the whole charging process within and outside the FCS in long-term operation. The proposed work will be extended for analysis with charging resource aggregation and different UEV categories. Charging coordination strategies will be further improved to reduce preempting probability of UEVs with mobile chargers. Utilization of mobile chargers will be further analyzed to enhance the charging reliability of EVs.

Author Contributions: K.M.S.Y.K.: conceptualization, methodology, software, formal analysis, validation, writing—original draft preparation; M.L.K.: supervision, conceptualization, methodology, formal analysis; N.U.-M.: co-supervision, conceptualization, methodology; I.A.M.B.: software, formal analysis. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: This study did not require ethical approval.

Informed Consent Statement: Not applicable

Data Availability Statement: Not applicable

Conflicts of Interest: The authors declare no conflict of interest.

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