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Reliability Enhancement of Fast Charging Station under Electric Vehicle Supply Equipment Failures and Repairs

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Abstract: This work focuses on the enhancement of the charging reliability of both scheduled (SEVs) and opportunistic (UEVs) electric vehicle (EV) users in an EV fast charging station (FCS). The proposed charging coordination strategies allow UEVs to exploit unused charging resources to optimally utilize the limited charging resources of FCS. However, the optimum utilization of limited charging resources of an FCS while assuring a reliable charging process for plugged-in EVs under random failures of electric vehicle supply equipment (EVSE) is a real challenge for the FCS controller. When the FCS admits UEVs in addition to SEVs, assuring a satisfactory quality of service to both EV user categories is also dispensable. Therefore, we analyze the performance of reservation of off-board mobile chargers (MOBCs) to enhance the charging reliability of EV users while achieving high charging resource utilization. This work proposes resource allocation and charging coordination strategies for an FCS where MOBCs are used to enhance the charging reliability of both SEVs and UEVs. Moreover, the proposed dynamic charging resource coordination strategies are analyzed with a continuous time Markov-chain (CTMC). The presented results from the CTMC model demonstrate that the proposed strategies outperform the EV charging process of the FCS in terms of high resource utilization and reliability while guaranteeing a satisfactory quality of service to EV users.

Keywords: electric vehicles; DC fast charging; charging reliability; charging resource availability; EV user satisfaction

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1. Introduction

Electric transportation significantly reduces environmental and health hazards caused by vehicular contaminant emissions. The proliferation of electric vehicles (EVs) in place of fossil-fueled vehicles contributes to accomplishing affordable, reliable and sustainable modes of transportation while achieving the United Nations' sustainable development goals (SDGs) in terms of mobility [1]. However, reaching to the net-zero emission targets defined by International Energy Agency (IEA) still remains an enormous challenge as the current EV market share is far away from what requires [2–4].

In this context, DC fast-charging stations (FCSs) are gaining increasing popularity among the majority of stakeholders in e-mobility due to the perceptible advancements of EV batteries and fast-charging technologies. The high energy and power-dense batteries and modern energy conversion technologies motivate the rapid deployment of FCS [5–7]. Sparsely deployed FCSs may promote the wholesale market adoption of lightweight EVs as they can have a similar refueling experience to their gasoline counterparts [8]. Although widening the FCS network in a region would provide effective solutions to charging and range concerns pertaining to long trips instead of requiring costly high-capacity EVs, the high penetration of FCSs poses substantial impacts on the power grid operation and energy market. Therefore, to cope with the issues related to power quality, network capacity and energy market caused by high penetration of FCSs, it necessitates costly grid reinforcements or reconstructions [9–12].

However, these costly grid reinforcements and reconstructions can be avoided by integrating a renewable energy system (RES) or energy storage (ES) into the FCS [13–15]. Therefore, the dedicated RES or ES together with the grid supply ensures the uninterruptible supply to EV chargers at FCS. Usually, the energy and power density of EV batteries depend on the battery technology. The battery capacity of most commercial EV models ranges from 10 kWh to 100 kWh along with specific charging constraints [16]. Therefore, this distinct charging demand has to be taken into consideration to develop energy-efficient FCSs. To cope with a wide range of charging demands, the ICE61851 [17] and ICE62196 [18] standards contemplate a wide range of DC-fast chargers capable of providing fast and ultra-fast charging. Usually, the EV charging process takes several minutes to a few hours depending on the EV capacity, charging constraints of EV batteries, the current state of charge (SoC) and EV user preferences. Therefore, it necessitates a charging coordination scheme to effectively utilize limited charging resources without excreting unnecessary stresses to the power grid.

In this context, extensive research efforts have been devoted to coordinating the charging process at a CS considering various objectives such as economic aspects, operational aspects, service quality aspects, etc. Furthermore, most of the charging scheduling schemes presented in the literature use layered architecture in which different objectives/aspects can be addressed at different hierarchical layers [19]. In most of the presented deterministic charging scheduling problems, authors have assumed that the input data for the problem are accurately known in advance [19–21]. Various possible uncertainties associated with EV charging process is illustrated in Figure 1. Due to these uncertainties, limited charging resources might not be optimally utilized in real-time operation.

In order to address these uncertainties, authors have employed several techniques to optimally schedule EVs at the CS. Authors in [22,23] propose a hierarchical approach to schedule EVs at CS as an online–offline mixed strategy. Mobility-related uncertainties are managed with a real-time heuristic algorithm with less computational overhead. Refs. [24,25] execute the proposed static algorithm iteratively to cope with the stochastic nature of the EV charging process. To minimize the revenue loss due to cancellations of scheduled charging and unexpected departures, authors have proposed multi-aggregator collaborative scheduling. As the EV demand can be shared among multiple aggregators in these strategies, the peak load caused by high penetration of EVs can be smoothened at the power grid level [26]. In EV charging coordination, the number of EV supply equipment (EVSE) or chargers plays a major role in relation to the quality of EV charging in terms of EV blockage, preemptage, reliability, availability, etc.

The authors of [27,28] have considered limited charging resources to propose their charging scheduling strategies. Although they have considered the charging station capacity in their analysis, focused attention to the limited number of chargers/EVSE has not been given. In a more realistic charging coordination scheme, the number of chargers/EVSE and their individual capacity put another constraint to the charging coordination. Nevertheless, due to various uncertainties shown in Figure 1, limited charging resources including both energy resources and chargers/EVSE might not be optimally utilized by the registered/scheduled EV users in real-time operation. Moreover, treating the charging processes with a few minutes duration (long-trip drivers or ultra-fast charging users) as opportunistic charging processes instead of scheduled ones would be more realistic. Although substantial research efforts have been devoted to the optimal scheduling of EVs at a CS, how to effectively exploit unused limited charging resources by scheduled users (SEVs) under uncertain conditions to further enhance resource utilization is not adequately analyzed to the best of the authors' knowledge. Furthermore, due to random failures and repairs of EVSE, the capacity of the FCS would be uncertain to maintain high availability for EV arrivals and high reliability for plugged-in EV users. If we ignore random failures of EVSE, we overestimate the average capacity of the FCS to analyze charging resource coordination. Therefore, we propose an event-based dynamic charging resource coordination strategy with a focus on the impact of random EVSE failure and repair so that opportunistic ultra-fast charging users (UEVs) can exploit limited charging resources unused by SEVs. This work is a continuation of our previous works presented in [29–31].

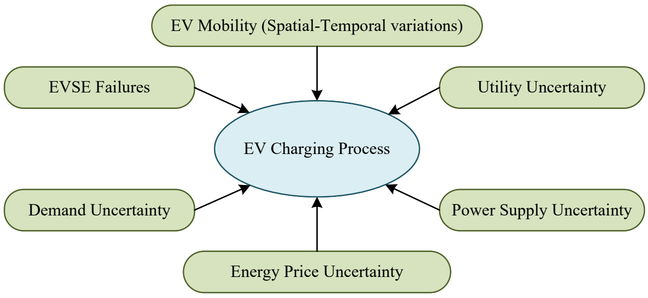

Figure 1. Uncertain aspects for EV charging process [31].

Consequently, the novel technical contribution and the goal of this paper are to propose a dynamic charging resource allocation and coordination strategy for both registered SEVs and opportunistic UEVs together with MOBCs and to analyze the reliability enhancement of FCS under EVSE failure and repair. In this work, we employ the continuous-time Markov-chain (CTMC) approach to model the proposed strategies.

2. Dynamic Charging Resource Allocation under EVSE Failure

Figure 2 illustrates the under-utilization and capacity reduction of a FCS due to various uncertainties associated with EV charging including EVSE failures. When we consider the charging resource utilization of scheduled EVs (SEVs) at a FCS, limited charging resources might not be optimally utilized due to various uncertainties illustrated in Figure 1. This wasted energy can be compensated by allowing opportunistic ultra-fast charging EV users (UEVs) along with SEVs. At the same time, we should note that EVSE are susceptible to fail due to hardware failures or protection issues.

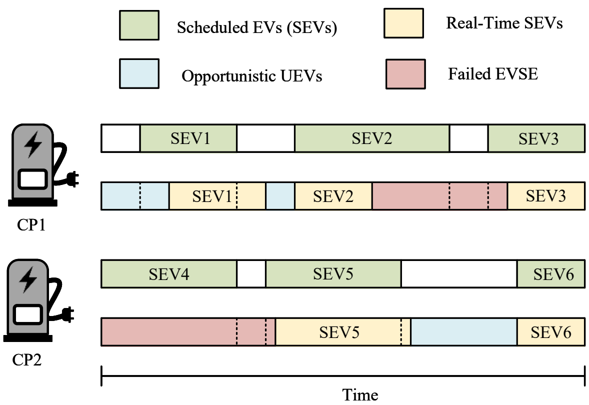

Figure 2. Utilization of charging resources by UEVs [31].

Owing to those failures of EVSE, the capacity of FCS or the effective number of plugged-in and charged EVs (throughput) decreases and the average charging time may rise. If we evaluate the FCS's performance without considering this downtime of EVSE, it overestimates the FCS capacity and performance. In this work, we focus on dynamic charging resource allocation and coordination for opportunistic UEVs along with SEVs under EVSE failure and repair as depicted in Figure 3.

Basically, two types of EV users are considered: (1) SEVs and (2) UEVs with distinct privileges and constraints in accessing the FCS as tabulated in Table 1.

Table 1. Access privileges and constraints of EV users.

SEVs	UEVs
• Pre-scheduled charging process	• Opportunistic charging
• 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 on arrival.	• Charger is assigned if sufficient resources are available only.
• Hardly subject to blockages	• Subject to blockages
• Charging process regularly finishes.	• Charging process is liable to be preempted before regularly finishes.
• Prioritized users at the MOBCs	• Charging process is liable to be preempted at the MOBCs.
• Expect uninterruptible EV charging	• Expect to charge as quickly as possible

The operation mechanism of FCS under EVSE failure and repair is illustrated in Figure 3.

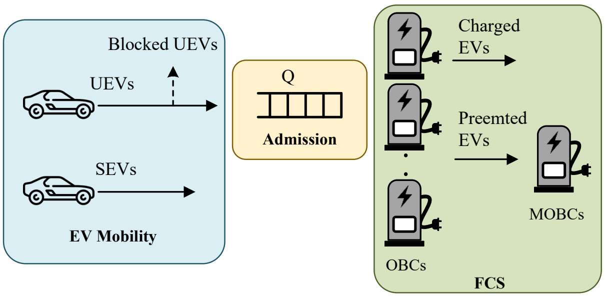

Figure 3. Proposed operating mechanism of the FCS [31].

In this work, we have considered an already deployed FCS with M; $(M \in \mathbb{Z}^+)$ number of off-board chargers (OBCs) and N; $(N \in \mathbb{Z}^+)$ number of off-board mobile chargers (MOBCs), that are used to enhance the reliability of the ongoing charging processes. It is assumed that the charging power of each OBC and MOBC can be adjustable. The FCS schedules and executes the charging processes of SEVs in line with EV user preferences. In the meantime, the FCS admits opportunistic UEVs to exploit non-utilized limited charging resources. In this work, we consider that SEVs are charged at a specified charge rate of P_s; $P_s \in [P_s^{min}, P_s^{max}]$ while UEVs are charged at nP_s depending on the charging resource availability at arrival. The value n is chosen such that nP_s is less than the rated power output of an OBC/MOBC (P_c^{max}); $nP_s^{max} \leq P_c^{max}$. Consequently, the capacity of the FCS becomes MP_s^{max}. SEVs demand an uninterruptible charging process whereas UEVs are liable to be interrupted upon the arrival of SEVs if the charging resources are not adequate. MOBCs identical to OBCs are deployed to retain ongoing charging processes without affecting from EVSE failures.

3. Methods

This work intends to develop a performance assessment framework using a CTMC model to evaluate the performance of a FCS in terms of reliability under EVSE failure and repair.

The charging coordination of FCS takes place in main three stages: (1) Optimal scheduling of SEVs to maximize the profit. They utilize charging resources as primary users. (2) Admitting UEVs as secondary users to exploit non-utilized limited charging resources. (3) Shifting interrupted charging processes due to EVSE failures and preemption of UEVs to MOBCs. In this work, we analyze the impact of opportunistic secondary users over SEVs and themselves under effective FCSs' capacity changes due to EVSE failures.

3.1. Stochastic EV Mobility Model

The performance of the FCS with proposed charging coordination strategies is analyzed using a CTMC model. Therefore, the following assumptions are made to develop the CTMC analytical model.

- Both SEV and UEV arrivals 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 and MOBCs are homogeneous and the service time of an EVSE is exponentially distributed with the service rate of μ_c. (μ_c rate denotes the average number of charged EVs per EVSE per unit time);
- All failures are homogeneous. The inter-failure time (during which an OBC functions well) of an OBC is exponentially distributed with a failure rate of λ_f per EVSE;
- The repair time of an OBC is exponentially distributed, with a repair rate per EVSE of μ_r.

In order to develop the CTMC analytical model to asses the reliability of FCS under EVSE failures, the following events are considered for state transitions; (1) SEV Arrivals at FCS, (2) SEV Departures from FCS, (3) UEV Arrivals at FCS, (4) UEV Departures from FCS, (5) Failure of EVSE to which an SEV is connected, (6) Failure of EVSE to which a UEV is connected, (7) Idle OBC failure, and (8) Repair of a failed EVSE. In the CTMC model, we have defined a generic state $\mathbf{x}$; $\mathbf{x} = \left\{x_s, x_u, x_{sm}, x_{um}, x_f\right\}$ to model system dynamics at each event aforementioned. In a generic state $\mathbf{x}$, x_s and x_{sm} denote the number of SEVs plugged-into normal OBCs and MOBCs, respectively. The numbers of UEVs plugged into normal OBCs and MOBCs are denoted by x_u and x_{um}, respectively. Furthermore, x_f indicates the number of failed OBCs at FCS.

3.2. Dynamic Charging Coordination Model

Initially, the set of feasible states of the system ($\mathbf{S}$) is obtained from the whole state space. $\mathbf{S} = \{\mathbf{x} | x_s, x_u, x_{sm}, x_{um}, x_f \geq 0;\ x_s \leq M,\ x_u \leq \lfloor(M/n)\rfloor,\ x_{sm} \leq N,\ x_{um} \leq \lfloor(N/n)\rfloor\ x_f \leq M,\ \sum(x_s, nx_u) \leq M,\ \sum(x_s, x_u, x_f) \leq M,\ \sum(x_{sm}, nx_{um}) \leq N\}$. The level of charging resource aggregation by UEVs is up to n steps as per the charging resource availability. The state transitions (STs) triggered by the aforementioned events at the FCS are described in the subsequent subsections. Power utilization of EVs and EVSE utilization of normal and mobile OBCs are expressed in (1)–(3), respectively.

$$a(\mathbf{x}) = x_s + nx_u + x_f \tag{1}$$

$$b(\mathbf{x}) = x_s + x_u + x_f \tag{2}$$

$$c(\mathbf{x}) = x_{sm} + x_{um} \tag{3}$$

3.2.1. Arrivals of EVs at FCS

Arrivals of SEVs (ASEVs) and UEVs (AUEVs) at FCS are considered in this Section. The STs triggered due to the ASEVs and AUEVs are tabulated in the ST Table 2. It is considered that the FCS is obliged to allocate charging resources immediately after arrival of an SEV as they have prior-agreements. Consequently, upon an arrival of an SEV, if there is at least one idle OBC, the SEV is plugged in without disrupting others. Otherwise, any ongoing UEV charging process must be interrupted. However, this interrupted UEV can be shifted to MOBCs if there is at least one idle EVSE. Otherwise, the concerned UEV charging process has to be preempted.

Moreover, in an occasion where all OBCs are occupied by SEVs, newly arrived SEVs must be blocked. The destination states related to STs triggered by SEV arrivals with respect to the generic state $\mathbf{x}$ at λ_s transition rate (TR) are tabulated in Table 2. The FCS accepts UEVs if SEVs do not occupy all the OBCs. Upon a new UEV arrival at the FCS, it is plugged in, if at least one OBC and enough energy resources are available to provide a charging power of P_u^{max}. Otherwise, the UEV has to be blocked as the charging processes of plugged-in UEVs are not preempted upon the arrival of the new UEV. Similarly the STs triggered due to the arrivals of UEVs are tabulated in the ST Table 2. The corresponding STs are taken place at λ_u TR.

Table 2. STs from **x** triggered by EV arrivals.

Conditions		Destination State	ST Rate
ASEVs, at least one idle OBC	$M - a(\mathbf{x}) > 0$;	$\{x_s + 1, x_u, x_{sm}, x_{um}, x_f\}$	λ_s
ASEVs, FCS is full. UEVs exist. idle MOBC exist	$M - a(\mathbf{x}) = 0; x_u > 0$; $c(\mathbf{x}) < N$;	$\{x_s + 1, x_u - 1, x_{sm}, x_{um} + 1, x_f\}$	λ_s
ASEVs, FCS is full. UEVs exist No idle MOBCs	$M - a(\mathbf{x}) = 0; x_u > 0$; $c(\mathbf{x}) = N$;	$\{x_s + 1, x_u - 1, x_{sm}, x_{um}, x_f\}$	λ_s
ASEVs, FCS is full. UEVs exist No idle MOBCs	$M - a(\mathbf{x}) = 0; x_u > 0$; $c(\mathbf{x}) = N$;	$\{x_s + 1, x_u - 1, x_{sm}, x_{um}, x_f\}$	λ_s
ASEVs, FCS is full. No UEVs	$M - a(\mathbf{x}) = 0; x_u = 0$;	$\{x_s, x_u, x_{sm}, x_{um}, x_f\}$	λ_s
AUEVs, at least one idle OBC Enough CRs available	$M - a(\mathbf{x}) \geq n$	$\{x_s, x_u + 1, x_{sm}, x_{um}, x_f\}$	λ_u
AUEVs, FCS is full.	$M - a(\mathbf{x}) < n$;	$\{x_s, x_u, x_{sm}, x_{um}, x_f\}$	λ_u

3.2.2. Departures of EVs from FCS

Departures of SEVs (DSEVs) and UEVs (DUEVs) from the FCS are considered in this section. Upon completion of charging, both SEVs and UEVs depart from the FCS, leaving an idle OBC or MOBC. As one UEV aggregates charging resources of n OBCs, it releases such amount of charging resources at the departure. A similar situation happens for MOBCs as well. The corresponding STs from **x** upon a departure of EV under the conditions aforementioned are tabulated in Table 3.

Table 3. STs from **x** triggered by EV Departures.

Conditions		Destination State	ST Rate
DSEVs from an OBC	$x_s > 0$;	$\{x_s - 1, x_u, x_{sm}, x_{um}, x_f\}$	$x_s\mu_{cp}$
DUEVs from an OBC	$x_u > 0$;	$\{x_s, x_u - 1, x_{sm}, x_{um}, x_f\}$	$x_u\mu_{cp}$
DSEVs from an MOBC	$x_{sm} > 0$;	$\{x_s, x_u, x_{sm} - 1, x_{um}, x_f\}$	$x_{sm}\mu_{cp}$
DUEVs from an MOBC	$x_{um} > 0$;	$\{x_s, x_u, x_{sm}, x_{um} - 1, x_f\}$	$x_{um}\mu_{cp}$

3.2.3. EVSE Failures and Repairs

In order to retain ongoing charging processes during the failures of EVSE, a limited number of MOBCs are placed at the FCS. When it comes to failures of EVSE, STs are considered depending on the user category of the EV connected with the failed EVSE. At a failure of EVSE, initially the FCS seeks an idle OBC regardless of the EV user category and if it fails only the EV is shifted to MOBCs. At a failure of SEV connected EVSE (FSEV), it obtains a high priority to continue the charging process at MOBCs. If it can find an idle MOBC, the SEV is shifted to MOBCs without interrupting any ongoing UEV charging process. Otherwise, an UEV (if any) has to terminate its charging process at MOBCs and donate the MOBC to the SEV. Still, if it fails, the SEV charging process has to be terminated. However, at a failure of UEV connected EVSE (FUEV), the UEV is shifted to MOBCs if an idle MOBC is available only. The STs triggered because of the failures and repairs of EVSE are tabulated in ST Table 4.

Table 4. STs from **x** triggered by EVSE failures and repairs.

Conditions		Destination State	ST Rate
Idle EVSE Failure	$M-b(\mathbf{x})>0$;	$\{x_s, x_u, x_{sm}, x_{um}, x_f+1\}$	$\lambda_f(M-b(\mathbf{x}))$
FSEVs, idle OBC exists	$M-b(\mathbf{x})>0$; $x_s>0$;	$\{x_s, x_u, x_{sm}, x_{um}, x_f+1\}$	$\lambda_f x_s$
FSEVs, no idle OBC idle MOBC exists	$M-b(\mathbf{x})=0$; $x_s>0$; $c(\mathbf{x})<N$;	$\{x_s-1, x_u, x_{sm}+1, x_{um}, x_f+1\}$	$\lambda_f x_s$
FSEVs, no idle MOBC UEVs are at MOBCs	$M-b(\mathbf{x})=0$; $x_s>0$; $c(\mathbf{x})=N$; $x_{um}>0$;	$\{x_s-1, x_u, x_{sm}+1, x_{um}-1, x_f+1\}$	$\lambda_f x_s$
FSEVs, no idle MOBC No UEVs are at MOBCs	$M-b(\mathbf{x})=0$; $x_s>0$; $c(\mathbf{x})=N$; $x_{um}=0$;	$\{x_s-1, x_u, x_{sm}, x_{um}, x_f+1\}$	$\lambda_f x_s$
FUEVs, idle OBC exists	$M-b(\mathbf{x})>0$; $x_u>0$;	$\{x_s, x_u, x_{sm}, x_{um}, x_f+1\}$	$\lambda_f x_u$
FUEVs, no idle OBC idle MOBC exists	$M-b(\mathbf{x})=0$; $x_u>0$; $c(\mathbf{x})<N$;	$\{x_s, x_u-1, x_{sm}, x_{um}+1, x_f+1\}$	$\lambda_f x_u$
FUEVs, no idle MOBC	$M-b(\mathbf{x})=0$; $x_u>0$; $c(\mathbf{x})=N$;	$\{x_s, x_u-1, x_{sm}, x_{um}, x_f+1\}$	$\lambda_f x_u$

3.3. FCS Centric Performance Evaluation Parameters

In this work, we analyze the charging reliability of FCS under EVSE failure and repair as an event driven model. We model the FCS operation and proposed charging resource coordination scheme using CTMC with continuous time and discrete states. The performance of the proposed charging coordination strategies are analyzed in terms of reliability. System dynamics are studied with the steady state probability vector $(\pi(\mathbf{x}))$ that gives the steady state probability of being in the corresponding state $\mathbf{x}$. To derive the $(\pi(\mathbf{x}))$, we use the global balance equation and the normalization equation expressed in (5). In (5), Φ is the TR matrix where non-diagonal elements $(\varphi_{x_i x_j}\ ; x_i, x_j \in \Phi)$ are calculated by obtaining the summation of TRs that are corresponding to all possible STs from x_i to x_j. Diagonal elements $(\varphi_{x_i x_i})$ of Φ are found using (4). The elements of TR matrix Φ depend on the arrival rates of SEVs, UEVs, service rate of chargers, number of chargers available at the FCS and charging resource aggregation levels. With the proposed charging resource allocation and coordination strategies, the aforementioned parameters are used as the inputs to the CTMC model. The CTMC model is developed in a generic nature so that any dynamic condition associated with the proposed charging coordination strategies can be analyzed.

$$\varphi_{x_i x_i} = -\sum_{x_j \in \Omega, j \neq i} \varphi_{x_i x_j}\ ;\ x_i, x_j \in \Omega \tag{4}$$

$$\pi\Phi = 0, \sum_{\mathbf{x} \in \Omega} \pi(\mathbf{x}) = 1 \tag{5}$$

For the long-term sustainable operation of the FCS, the availability of FCS and reliability of charging processes under random EVSE failures and repairs are very indispensable. Reliability and availability aspects are very essential for the FCS to provide high-quality service to EV users. In this section, the performance parameters for the reliability and availability are derived in terms of $\pi(\mathbf{x})$.

3.3.1. Availability of FCS for EVs (A)

FCS accepts UEVs opportunistically to enhance the utilization of limited charging resources, but there may be occasions where a charging request from a UEV is blocked due to limited or unavailability of charging resources. Under such situations, the FCS is said to be unavailable for new UEVs. Even the FCS might not be available for SEVs if they arrive in time periods other than scheduled ones. Therefore, availability-related performance assessments are very important for both SEVs and UEVs. In this paper, we define the availability of FCS for UEVs as the probability that the FCS allocates charging resources for newly arrived UEVs without any failure.

Let (A_{uev}) denote the availability of FCS for UEVs, then A_{uev} can be expressed as in (6). However, as SEVs are registered users, they have a high priority in accessing the

FCS. Generally, it is considered that the FCS is available for SEVs when they arrive in the scheduled time. However, If all OBCs are occupied by SEVs, the FCS is not available for newly arrived SEVs. Therefore, the EVSE availability for SEVs is obtained by (7).

$$A_{uev} = 1 - \sum_{\substack{\mathbf{x}\in\Omega, \\ M-a(\mathbf{x})\geq n,\ M-b(\mathbf{x})>0}} \pi(\mathbf{x}) \tag{6}$$

$$A_{sev} = 1 - \sum_{\substack{\mathbf{x}\in\Omega,\ x_s=b(\mathbf{x}), \\ a(\mathbf{x})=M,\ M-b(\mathbf{x})=0}} \pi(\mathbf{x}) \tag{7}$$

3.3.2. Reliability of Charging Process (R)

The ability of a charging process to retain its operational state without being interrupted by any means until it regularly finishes is defined as the reliability of a charging process. Upon a failure of an EVSE, the corresponding charging process has to be preempted if idle OBCs are not available irrespective of EV user type. Nevertheless, charging processes of UEVs are liable to be preempted if charging resources are not adequate to admit SEVs. Therefore, the probability that an ongoing charging process, once commenced, continues to operate without interruptions until regularly finish can be used to quantitatively express the reliability of the charging process.

Due to random failures of EVSE, the charging processes of both SEVs and UEVs can be affected. When considering the charging reliability of UEVs, the charging process of an UEV has to be preempted in the following three cases: (1) SEV-connected OBC fails and either an idle OBC or MOBC is not available. (2) UEV-connected OBC fails and either an idle OBC or MOBC is not available. (3) Upon the arrival of a new SEV, all OBCs are occupied and an idle MOBC is not available. Therefore, in order to find the charging reliability of each user category, firstly we need to find the mean preempting rate of UEVs $(\dot{\alpha}_{uev})$ for the aforementioned three cases. Therefore, the mean preempting rates of UEVs in those three cases $(\dot{\alpha}_{uev1})$, $(\dot{\alpha}_{uev2})$ and $(\dot{\alpha}_{uev3})$ are derived as expressed in (8)–(10), respectively. We can derive the preempting probability of an EV user type by obtaining the ratio between the mean preempting rate $(\dot{\alpha})$ and the corresponding plugging rate $(\dot{\beta})$. The mean plugging rate of UEV $(\dot{\beta}_{uev})$ can be obtained as $\lambda_u A_{uev}$. Therefore, the charging reliability of UEV charging process (R_{uev}) can be expressed as (11).

$$\dot{\alpha}_{uev,1} = \sum_{\substack{\mathbf{x}\in\Omega, \\ b(\mathbf{x})=M,\ c(\mathbf{x})=N, \\ x_s>0\ x_{um}>0}} x_s \lambda_f \pi(\mathbf{x}) \tag{8}$$

$$\dot{\alpha}_{uev,2} = \sum_{\substack{\mathbf{x}\in\Omega, \\ b(\mathbf{x})=M,\ c(\mathbf{x})=N, \\ x_u>0}} x_u \lambda_f \pi(\mathbf{x}) \tag{9}$$

$$\dot{\alpha}_{uev,3} = \sum_{\substack{\mathbf{x}\in\Omega, \\ a(\mathbf{x})=M,\ c(\mathbf{x})=N, \\ x_u>0}} \lambda_s \pi(\mathbf{x}) \tag{10}$$

$$R_{uev} = \frac{\sum_{i=1}^{3} \dot{\alpha}_{uev,i}}{\lambda_u A_{uev}} \tag{11}$$

It is very important to analyze the charging reliability of SEVs (R_{sev}) as well. The mean preempting rate of SEVs $(\dot{\alpha}_{sev})$ can be obtained as in (12) under EVSE failures. The plugging rate of SEVs $(\dot{\beta}_{sev})$ can be obtained as $\lambda_s A_{sev}$. Therefore, the charging reliability of SEV charging process (R_{sev}) is expressed as (13).

$$\dot{\alpha}_{sev} = \sum_{\substack{\mathbf{x}\in\Omega,\\ b(\mathbf{x})=M,\ c(\mathbf{x})=N,\\ x_s>0\ x_{um}=0}} x_s \lambda_f \pi(\mathbf{x}) \tag{12}$$

$$R_{sev} = \frac{\dot{\alpha}_{sev}}{\lambda_s A_{sev}} \tag{13}$$

The presented CTMC analytical model assesses the availability of FCS for EVs and the reliability of the charging process with the proposed dynamic charging resource coordination strategies.

4. Results and Discussion

The reliability of the ongoing EV charging process and availability of FCS for new EV arrivals under EVSE failures and repairs are analyzed in this work. This section elaborates on the behavior of FCS with MOBCs under EVSE failures. In this section, we have incorporated derived expressions for A and R in Section 3.3. To analyze the performance of the developed charging coordination strategies, we have considered a scenario where the FCS is equipped with 10 CPs (i.e., $M = 10$) whose charging power can be adjusted within a specified range in steps. Typically, available fast-charging EVs can be charged at a charging rate ranging from 50 kW to 400 kW. Therefore, it can be assumed that ultra-fast charging EVs can be charged at a twofold aforementioned fast charging rate. The CTMC parameter n is set to 2. (The CTMC parameters are defined in Section 2).

4.1. Reliability of UEVs

In this scenario, an ongoing charging process of UEV can be preempted due to the unavailability of resources upon the arrival of a new SEV or EVSE failure. In this Section, we analyze the charging reliability of both SEVs and UEVs. We plot the charging reliability of SEVs and UEVs under EVSE failure by considering the derived equation in Section 3.3.2. Figure 4 shows the charging reliability of UEVS as λ_s varies. In Figure 4, we have analyzed the charging reliability of UEVs for different λ_u when λ_s varies from 0 to 60 h^{-1}. The charging reliability of UEVs decreases with the increment of λ_u. At lower λ_s, a charging process of an UEV is unlikely to be preempted due to the under-utilization of charging resources. Figure 4 very clearly illustrates that the charging reliability of UEVs can significantly be improved with reserved MOBCs. For instance, when λ_s = 60 h^{-1} and λ_u = 42 h^{-1}, the proposed charging coordination scheme with MOBCs has improved the charging reliability of UEVs by 56% compared that of FCS without MOBCs. Figure 4 also depicts that a higher charging reliability of UEVs can be achieved with more MOBCs at a cost of under-utilization.

4.2. Reliability of SEVs

Unlike in UEVs, the charging reliability of SEVs is significantly high due to their prior agreements with FCS. However, an ongoing charging process of an SEV has to be preempted upon an EVSE failure if there is no any idle OBC or ongoing UEV charging process. Figure 5 depicts the charging reliability of SEVs as λ_F varies. According to defined charging coordination strategies, the charging reliability of SEVs does not depend on the increment of λ_u. Figure 5 very clearly illustrates that the charging reliability of SEVs can significantly be improved with reserved MOBCs. For instance, when λ_F = 0.6 h^{-1}, the proposed charging coordination scheme with MOBCs has improved the charging reliability of SEVs by 91% compared that of with FCS without MOBCs.

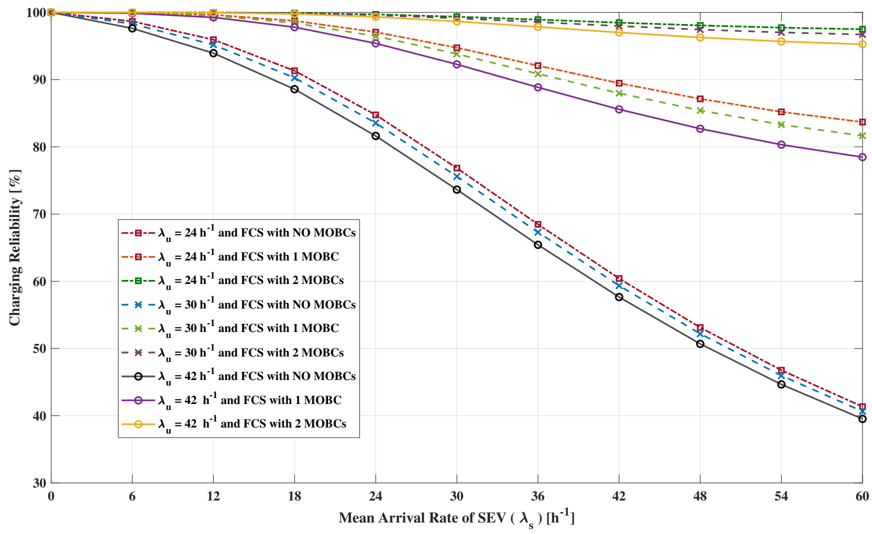

Figure 4. Reliability of charging completion of UEVs as a function of λ_s.

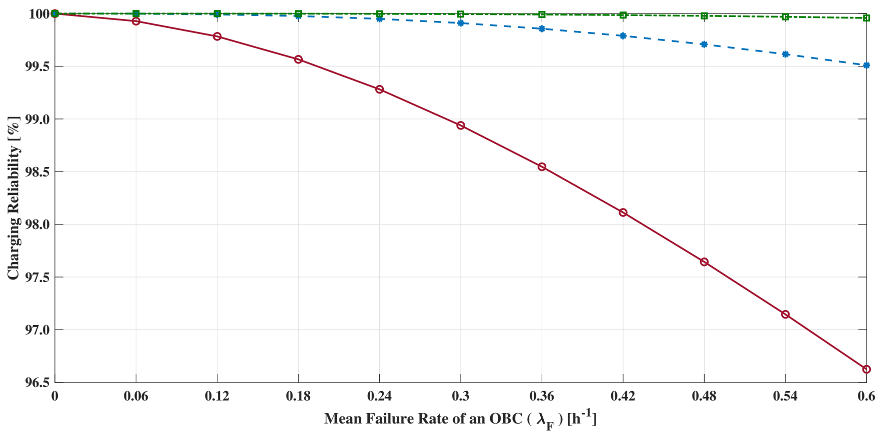

Figure 5. Reliability of charging completion of SEVs as a function of λ_F.

4.3. Availability of FCS SEVs

We intend to analyze how MOBCs enhance the availability and reliability of the FCS under EVSE failures and repair. Figure 6 evaluates the availability of the FCS for UEVs under EVSE failures. Due to the prior agreement with the FCS, it is considered that the FCS is available for SEVs upon arrival. At lower λ_s, the FCS is available for SEVs even if they arrived out of the schedule. However, when λ_s increases, the availability of the FCS for UEVs decreases. According to the proposed charging resource coordination strategies, a newly arrived EV (SEV or UEV) will not be plugged into a MOBC. Figure 6 very clearly shows that the availability of the FCS for both SEV and UEV solely depends on the arrival rate of EVs.

With the presented results for selected scenarios, we have analyzed the charging reliability improvement of both SEVs and UEVs with proposed EV charging resource coordination strategies under EVSE failures and repairs. The presented results showed that reserving MOBCs at the FCS outperforms the charging reliability of both SEVs and UEVs under EVSE failures.

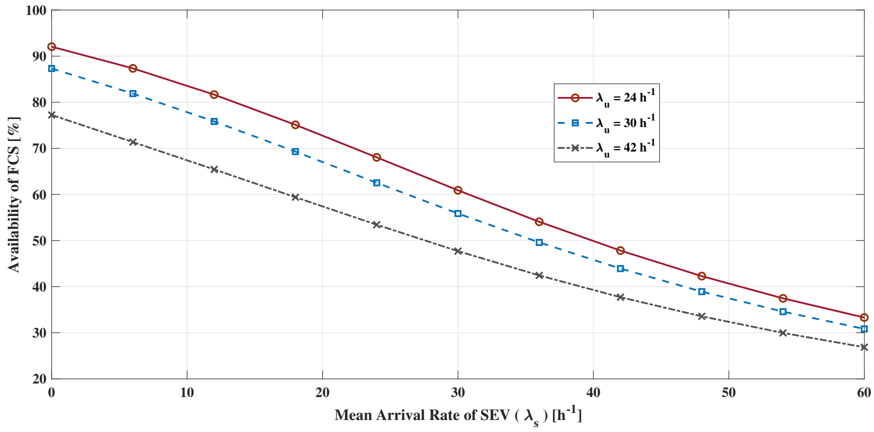

Figure 6. Availability of FCS for UEVs as a function of λ_s.

5. Conclusions

In this paper, we have analyzed how MOBCs can be incorporated to enhance the charging reliability of UEVs and SEVs. The proposed strategy enables UEVs to exploit unused charging resources allocated for scheduled EV users at FCS to enhance charging resource utilization. However, when increasing the arrival of SEVs and EVSE failures, the charging reliability of UEVs is severely affected. The presented results prove that reserving the limited charging resources as mobile chargers at the FCS can enhance the charging reliability of opportunistic EV users significantly. The proposed charging resource coordination strategies have improved the charging reliability of UEVs by 56% and SEVs by 91% in considered worst-case scenarios, compared to that of FCS without MOBCs.

Along with the proposed strategies, we have derived a framework in a generic nature using CTMC to assess the FCS-centric performance in terms of charging reliability and availability of FCSs. This FCS-centric performance assessment framework can be incorporated to ensure an undisturbed charging process for EV users. The proposed work will be extended for analysis with charging resource aggregation and different SEV categories. An operational profit analysis considering innovative price schemes for heterogeneous EV users is also further investigated.

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Abbreviations

EV	Electric vehicle
CS	Charging station
FCS	Fast charging station
SEV	Scheduled EV user
OEV	Opportunistic ultra-fast charging EV user
EVSE	EV supply equipment
OBC	Off-board EV charger
MOBC	Mobile Off-board EV charger

CP	Charging point
QP	Queue point
CTMC	Continuous-time Markov chain
RES	Renewable energy system
ES	Energy storage
ASEV	Arrival of a SEV
AUEV	Arrival of a UEV
DSEV	Departure of a SEV
DUEV	Departure of a UEV
FSEV	A failure of SEV connected EVSE
FUEV	A failure of UEV connected EVSE
TR	Transition rate
ST	State transition

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