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# Analysis and quality of service evaluation of a fast charging station for electric vehicles

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ABSTRACT

Electrification of transportation is considered as one of the most promising ways to mitigate climate change and reduce national security risks from oil and gasoline imports. Fast charging stations that provide high quality of service will facilitate the wide market penetration of electric vehicles. In this paper, the operation of a fast charging station is analyzed by employing a novel queuing model. The proposed analysis considers that the various electric vehicle models are classified by their battery size, and computes the customers' mean waiting time in the queue by taking into account the available charging spots, as well as the stochastic arrival process and the stochastic recharging needs of the various electric vehicle classes. Furthermore, a charging strategy is proposed according to which the drivers are motivated to limit their energy demands. The implementation of the proposed strategy allows the charging station to serve more customers without any increase in the queue waiting time. The high precision of the present analytical model is confirmed through simulations. Therefore, it may be utilized by existing fast charging station operators that need to provide high quality of service, or by future investors that need to design an efficient installation.



## 1. Introduction

The gradual replacement of Internal Combustion Engine (ICE) vehicles with Electric Vehicles (EVs) is highly promoted within the transportation sector [1]. A review of national targets forecasts an annual production of over 100 million EVs by 2050 [2]. The main advantage of the EVs is their potential to reduce the dependence on fossil fuels, as well as the emissions caused by fuel combustion [3]. The economic and environmental performance of EVs is particularly high when combined with sustainable power generation, and it is further improved when smart charging strategies and real time pricing schemes are implemented [4]. EVs can participate in Demand Response (DR) programs by operating either as controllable loads or as storage devices [5]. Therefore, they facilitate the integration of renewable energy systems into the grid [6], and contribute to the load variance smoothing in microgrids [7], especially when their charging management [8] is combined with optimal energy management schemes of other loads installed in the microgrids [9].

On the other hand, the main concern over the EV technology is the confrontation of drivers' range anxiety, which refers to EVs' short driving ranges and long charging durations [10]. Therefore, the large deployment of level 3 Fast Charging Stations (FCSs) is crucial for achieving public acceptance of EVs [11]. The Japanese standard CHArge de MOve (CHAdeMO) is currently the most popular option for DC fast charging, while the Combined Coupler Standard (CCS) is an emerging technology being promoted by Europe Automotive Industry [12]. Many manufacturers such as Nissan, Mitsubishi and Kia have equipped their EV models with the former technology [13], whereas other manufacturers such as BMW and Volkswagen use the latter [14]. Furthermore, Electric Vehicle Supply Equipment (EVSE) manufacturers have designed Charging Spots (CSs) that contain both a CHAdeMO and a CCS outlet in a single cabinet [15].

For EVs, the role of FCSs will be similar to that of gasoline stations for ICE vehicles. FCSs provide high power rates and as a result, the duration of charging an EV battery up to 80% of its rated capacity ranges between 0.2 and 1 h [16]. This is a relatively short amount of time when compared to the 11–36 h required using level

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**Nomenclature**

| | |
|---|---|
| $a$ | total load of the system |
| $a_c$ | load of $c$-class EVs |
| $a_{c1}$ | load of subclass $c_1$ EVs |
| $a_{c2}$ | load of subclass $c_2$ EVs |
| $a_{\max}$ | maximum load |
| $B_c$ | battery capacity of $c$-class EVs (kWh) |
| $C$ | number of EV classes |
| $c_v$ | coefficient of variation of the superposed charging time distribution |
| $d$ | discount offered to subclass $c_1$ EVs |
| $E_{EVs}$ | mean energy supplied to the EVs (kWh) |
| $F_c$ | arrival SoC CDF of $c$-class EVs |
| $G$ | CDF of the superposed charging time |
| $g$ | PDF of the superposed charging time |
| $G_c$ | CDF of $c$-class EVs charging time |
| $g_c$ | PDF of $c$-class EVs charging time |
| $h_c$ | market shares of EV classes |
| $k_c$ | probability that a $c$-class EV enters a CS |
| $k_{c1}$ | probability that a subclass $c_1$ EV enters a CS |
| $k_{c2}$ | probability that a subclass $c_2$ EV enters a CS |
| $L_{M/D/s}$ | mean number of customers waiting in the queue in an M/D/s system |
| $L_{M/G/s}$ | mean number of customers waiting in the queue in an M/G/s system |
| $L_{M/M/s}$ | mean number of customers waiting in the queue in an M/M/s system |
| $m$ | mean superposed charging time (h) |
| $m_c$ | mean charging time of $c$-class EVs (h) |
| $m_{c1}$ | mean charging time of subclass $c_1$ EVs (h) |
| $m_{c2}$ | mean charging time of subclass $c_2$ EVs (h) |
| $P_{EVs}$ | mean power drawn by the EVs (kW) |
| $P_{CS}$ | power rate of the CSs (kW) |
| $R$ | operator's revenue (€) |
| $R'$ | operator's revenue when the charging strategy is activated (€) |
| $r$ | energy price (€/kWh) |
| $r'$ | energy price for subclass $c_1$ EVs (€/kWh) |
| $s$ | number of CSs |
| $SoCA_c$ | arrival SoC of $c$-class EVs |
| $SoCD_c$ | departure SoC of $c$-class EVs |
| $SoCD_{thr}$ | departure SoC threshold when the charging strategy is activated |
| $T$ | superposed charging time (h) |
| $t$ | time (h) |
| $T_c$ | charging time of $c$-class EVs (h) |
| $v$ | variance of the superposed charging time distribution |
| $W$ | mean queue waiting of the EVs (min) |
| $W_q$ | QoS criterion for the queue waiting time (min) |
| $x_c$ | residual SoC increase of $c$-class EVs |
| $x_{c1}$ | residual SoC increase of subclass $c_1$ EVs |

*Greek symbols*

| | |
|---|---|
| $\gamma$ | increase in the arrival rate capacity when the charging strategy is activated |
| $\lambda$ | superposed arrival rate (EVs/h) |
| $\lambda_c$ | arrival rate of $c$-class EVs (EVs/h) |
| $\lambda_{c1}$ | arrival rate of subclass $c_1$ EVs (EVs/h) |
| $\lambda_{c2}$ | arrival rate of subclass $c_2$ EVs (EVs/h) |
| $\lambda_{c,max}$ | maximum arrival rate of $c$-class EVs (EVs/h) |
| $\lambda_{\max}$ | maximum arrival rate capacity (EVs/h) |
| $\lambda'_{c,max}$ | maximum arrival rate of $c$-class EVs (EVs/h) (the charging strategy is activated) |
| $\lambda'_{\max}$ | maximum arrival rate capacity (EVs/h) (the charging strategy is activated) |
| $\rho$ | utilization rate of the system |
| $\sigma_c$ | percentage of $c$-class EVs that accept the operator's offer |
| $\tau$ | time interval where the arrival rates are equal to their maximum values (h) |
| $\psi$ | correction function used for the calculation of the queue waiting time |

*Subscripts*

| | |
|---|---|
| $c$ | $c$-class EVs |
| $c_1$ | subclass $c_1$ EVs |
| $c_2$ | subclass $c_2$ EVs |

1 home equipment or to the 2–3 h required using level 2 equipment [16]. However, fast charging duration is considered to be long when compared to the duration of refilling ICE vehicles (1–3 min). This may result in the formation of queues and long waiting times, especially during peak-traffic hours when the number of charging requests is expected to be high. In turn, long waiting times may cause EV drivers' discomfort and dissatisfaction. It is therefore essential for FCS operators to develop mechanisms for queue waiting time estimation, through the consideration of the EVs' stochastic arrival and charging times.

For the stochastic modeling of the EVs' charging process, various queuing theory models have been utilized, with M/M/s being the most common of them. The advantage of this model is its simplicity, since the arrival process of the EVs is assumed to be Poisson (M), while the charging times of the EVs follow the exponential distribution (M). Finally, s denotes the number of CSs that the charging station facility contains [17]. The M/M/s queue is employed in Ref. [18] for estimating the charging load of a single FCS, as well as in Ref. [19] for calculating the charging load of a network of FCSs. The same queuing model is also applied for the calculation of the queue waiting time in a network of FCSs [20], as well as in a parking lot consisting of level 2 outlets [21]. On the other hand, the M/M/s/c queue is used for modeling a parking lot with finite waiting space in Ref. [22]. In this case, the QoS metrics under evaluation are both the queue waiting time and the blocking probability, i.e. the probability that an EV will not enter the parking lot due to lack of waiting space. The M/M/s/s queue is applied in Ref. [23] for modeling a FCS which draw a certain amount of power from the grid. Blocking probability is the only QoS metric in this case, since EVs are blocked when the available power in not enough to meet their demands. The same queuing model is also employed in Refs. [24], where it is considered that the charging station provides different charging power levels. In this case, EVs are classified by their charged power rate and the blocking probability for each EV class is then separately calculated.

However, the concept of classifying EVs by their different battery sizes is only considered in Ref. [25]. Nevertheless, the charging load of the charging station is calculated by applying a single class M/M/s queue. A key assumption in all aforementioned queuing models is that the EVs' charging times are exponentially distributed random variables. In real life though, charging times do not seem to follow any specific probability distribution, since they are mainly