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An Event-Based Simulation Framework to Examine the Response of Power Grid to the Charging Demand of Plug-In Hybrid Electric Vehicles

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***Abstract*—This paper describes the development of a discrete-event simulation framework that emulates the interactions between the power grid and plug-in hybrid electric vehicles (PHEVs) and examines whether the capacity of the existing power system can meet the PHEV load demand. The probability distribution functions for the arrival time and energy demand of each vehicle are extracted from real-world statistical transportation data. The power grid's limited generation and transmission capacities are considered to be the major constraints. Therefore, vehicles may have to wait to receive any charge. The proposed simulation framework is justified and described in some detail in applying it to two real cases in the United States to determine certain regions' grid potential to support PHEVs. Both Level-1 and -2 charging are considered.**

***Index Terms*—Charging event, load profile, plug-in hybrid electric vehicle (PHEV), power grid, transportation electrification.**

NOMENCLATURE:

BC_j	Battery capacity of vehicle j (kWh).
C_{grid}	Grid capacity limitation (kW).
CL	Charging level (kW).
C_{Idle}	Idle capacity (kW).
d_j	Distance driven by vehicle j (mile).
E_j	Energy required to fully charge vehicle j (kWh).
E_{Unmet}	Unmet energy.
GU	Giving-up event.
i	Event number.
j	PHEV number.
L	Amount of domestic load.
Np	Number of total outlets.
Np^I	Number of idle outlets.
Np^B	Number of busy outlets.
N^{PHEV}	Number of total PHEVs.
Nq	Number of PHEVs in the queue.
P^T	Total load.
PUF	Power grid usage factor.
r	Random value.
SOC_j	State of charge of vehicle j upon arrival.
t	Current time.
t_0	Start time of the simulation framework.
t_{end}	End time of the simulation framework.
t_w	Mean wait time of PHEVs.
T_j^{AR}	Arrival time of vehicle j.
T_j^{CS}	Charging-start time of vehicle j.
T_j^{CC}	Charging-complete time of vehicle j.
T_j^{GU}	Giving-up time of vehicle j.
x_j	All-electric range of vehicle j.
χ_j^{WA}	Waiting status of vehicle j.
χ_j^{PI}	Plugged-in status of vehicle j.
χ_j^{CC}	Charging-complete status of vehicle j.
χ_j^{GU}	Giving-up status of vehicle j.
λ	Arrival rate.
τ_j^{ch}	Charging duration time of vehicle j.
τ_j^{AR}	Inter-arrival time of vehicle j.
τ_j^{tol}	Tolerance duration of vehicle j.

I. INTRODUCTION

THE transportation sector is one of the major contributors to greenhouse gas emissions, urban air pollution, high energy prices, and the rapid depletion of fossil fuel resources. Concerns over the adverse impacts of conventional vehicles necessitate a cleaner and more efficient vehicle technology. Plug-in hybrid electric vehicles (PHEVs) are the most promising approach to sustainable transportation [1]–[6].

Although the penetration of PHEVs is not yet significant, their impact on the power grid already has been the subject of many research studies. The random nature of the charging behavior of a large number of PHEVs would introduce uncertainty into a power system's operation, particularly in cases of high

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penetration [7]. Given the opportunity, most PHEV owners will likely plug in their vehicles during afternoon hours [8]. Consequently, the electricity demand during those hours will increase, putting a significant load on the power grid. In an effort to quantify this scenario, it is necessary to examine the power grid from the following two perspectives: the degree to which the peak charge demand of the PHEV fleet overlaps the peak time of the domestic load profile and the degree to which the peak domestic load profile will exacerbate.

Several studies have evaluated the impact of PHEVs on the power grid from different angles. Most examine the capacity of the power grid to handle an extra load by comparing the relative change in the utility load profile with and without PHEV loads [9]–[12]. Studies using the valley-filling approach have claimed that 50%–73% of the American light duty fleet could be electrified using idle generation capacity. The potential of the power grid to charge PHEVs has been defined as the difference between the highest demand during the off-peak period and the system's maximum generation capacity [12]. Other studies have proposed optimization models for minimizing system costs and maximizing profit [13]–[19].

There are several challenges associated with PHEV fleet studies. Information about the number of vehicles, the size of their energy storage devices [20], their arrival time, and their daily distance driven must be available. Also, regarding the grid, one needs to know the domestic load profile, as well as the available number of charging stations and their charging level. Considering the scale of the system, finding or collecting reliable data often is difficult. Uncertainty arising from the availability and reliability of real-world data has led researchers to evaluate the impact of PHEVs using probabilistic approaches [21]–[25].

The study described here develops a discrete-event simulation framework for examining the power system's potential to meet the load demand of PHEVs. Real-world data available from the National Household Transportation Survey (NHTS) [26] are used to develop probability density functions (PDFs) for a vehicle's arrival time and required charge. NHTS includes a large amount of statistical transportation data collected from all over the U.S. [27]. The present work can be distinguished from the above-mentioned studies in three ways. First, statistical transportation data are used to determine not only a vehicle's plugging-in time but also the energy required to reach a full charge. Second, more details for calculating the state of charge (SOC) of the vehicles by considering the vehicle type and miles driven are provided. Third, this simulation framework first sets the power system constraints and then allows PHEVs to be charged as long as the constraints are not violated. This approach yields different metrics. For example, previous studies have determined how much the operating temperature of the distribution transformer would rise [24], [28], [29]. However, this study determines what percentage of vehicles could be served, as well as the wait time, given the existing capacity of the power system.

The remainder of this paper is organized as follows. Section II introduces the simulation framework of PHEV charging events and presents its concepts, inputs, workflows, and outputs. It also extracts the PDFs, which are the main inputs to the simulation framework. Then, Section III applies this simulation framework to two regions in the U.S. as case studies and summarizes the results. Finally, Section IV offers concluding remarks.

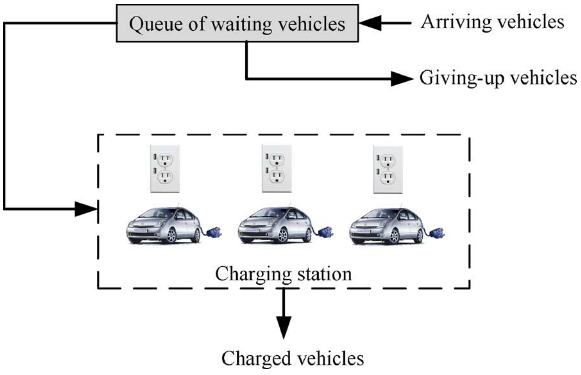

Fig. 1. Vehicles' different statuses in the simulation framework.

II. PHEV CHARGING EVENT SIMULATION FRAMEWORK

The developed simulation framework treats PHEV fleet charging as a series of stochastic events that occur in a chronological sequence according to a first-arrived, first-served policy. It treats the power grid as a collection of outlets. If the power demand approaches grid constraints, arriving PHEVs will be placed in a virtual queue, as shown in Fig. 1. The vehicles in the queue will either receive service if the overall load demand drops below grid constraints or eventually give up the attempt to receive a charge and leave the queue if the wait time is too long. The simulation framework yields the mean wait time, percentages of charged and uncharged PHEVs, and resulting load profiles. The concepts, inputs, workflows, and outputs of the system are described below.

A. Concepts

The proposed simulation framework includes the following concepts [30].

- **Entities:** Any object involved in the study (e.g., PHEVs, outlets, and the queue).
- **Attributes:** Properties of an entity; for example, one attribute of a PHEV is its SOC.
- **State Variables:** Values expressing the state of the system. Examples include the number of PHEVs in the system (either under charge or in the queue), the number of idle outlets, and a PHEV's status.
- **Events:** Occurrences that change the state of the system. For example, an arrival event increases the queue length, and a charging-complete event decreases the queue length.

Other concepts include the following.

- **Future Event List (FEL):** A list of future events that are ordered by the time at which they occur. The events are scheduled dynamically; that is, when one event occurs, the next event is scheduled. For example, when a PHEV arrives at time t and charging begins, the charging-complete event is scheduled for $t + \tau$ in the FEL, where τ is the charging duration time.
- **Clock:** A variable that determines the time during the simulation. Once the simulation has begun, the clock moves from zero to the time of the first event scheduled in the

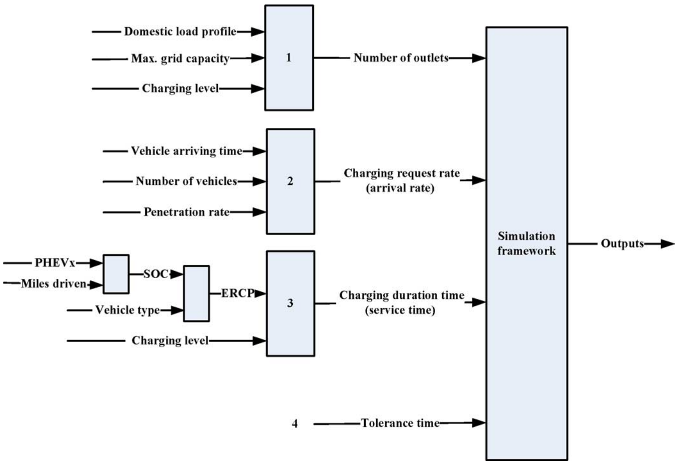

Fig. 2. Four inputs of the simulation framework.

TABLE I
CHARGING LEVELS

Level Standard	1	2	3
EPRI-NEC	120 VAC, 15 A, 1.44 kW	240 VAC, 40 A	480 VAC, 60 to 150 kW
SAEJ1772	120 VAC, 12 A, 1.44 kW	208-240 VAC, 32 A, 7.68 kW	208-600 VAC, 3-phase, > 7.68 kW

FEL. Based on this variable, the events in the FEL occur chronologically.

- **Statistics:** During the simulation run, statistical data are gathered. These data include the wait time for each PHEV, the length of the queue, or other pertinent information based on the objective of the study. The performance of the system is evaluated using this statistical data.

B. *Inputs*

The four inputs of the simulation framework are defined as follows: 1) the number of available outlets, which represents the idle capacity of the power grid; 2) the vehicle arrival time; 3) the charging duration time, which is the amount of time required to fully charge a vehicle; and 4) tolerance duration, which indicates how long a vehicle would wait before giving up. Fig. 2 depicts the block diagram in which the four inputs are determined.

1) Number of Available Outlets : The number of available outlets refers to the total number of PHEVs that can be serviced simultaneously at any given time. This number depends on the amount of the local load, the maximum grid capacity, and the available charging level (see block 1 in Fig. 2). Various studies have introduced several charging levels. For instance, [31] used standard 110 V/15 A and 240 V/30 A outlets, labeling them as providing a normal charging level and a quick charging level, respectively. Another study [32] used Belgian standard outlets (230 V, 4 kW). Table I represents two different sets of charging levels introduced by the Electric Power Research Institute (EPRI) and the Society of Automotive Engineering (SAE) J1772 standard, both of which are applicable in the U.S. and have been used by many studies [33]–[36]. This study uses SAEJ1772.

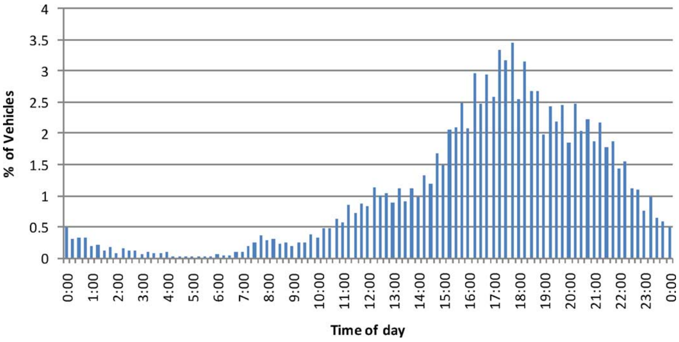

Fig. 3. Ninety-six arrival rates (λ) of vehicles.

A lower local load, a higher grid capacity, and a lower charging level permit more PHEVs to be plugged in at the same time. This is a deterministic and time-variant value calculated as

$$Np(t) = \frac{C_{\text{grid}} - L(t)}{\text{CL}} \quad (1)$$

where $Np(t)$ is the total number of outlets at time t, C_{grid} represents the power grid capacity limitation or maximum demand limitation [37], which could be determined based on the generation, transmission, and distribution capacities of the grid, depending on which one has the smallest capacity [38]. $L(t)$ is the domestic load at time t, and CL is the charging level (all three in kW). Also, one can write

$$Np(t) = Np^I(t) + Np^B(t) \quad (2)$$

where Np_t^I and Np_t^B are the numbers of idle outlets and busy outlets, respectively, at time t.

2) Vehicle Arriving Time: Vehicles arrive independently. Therefore, the number of vehicles arriving at time t is considered to follow a Poisson distribution. Consequently, the time between each pair of consecutive vehicle arrivals, i.e., inter-arrival time, has an exponential distribution with parameter λ [30]. Given a random value r drawn from the uniform distribution on the unit interval (0, 1), one can generate the inter-arrival time τ as

$$\tau = \frac{-1}{\lambda} \ln(r) \quad (3)$$

where λ is the arrival rate. In this study, the 2001 NHTS data are used to obtain the arrival rate. Fig. 3 suggests that this rate strongly depends on the time of day [39]. In this study, the 24-h cycle is divided into 96 equal intervals. The arrival rate during each 15-min time interval is considered to be constant. It is obtained from Fig. 3 scaled by the total number of vehicles in the region. The number of PHEVs in a specific region can be estimated based on the number of conventional cars in that region multiplied by the PHEV penetration rate. According to (3), the inter-arrival time between the arrival of vehicles j and $j+1$ is

$$\tau_j^{\text{AR}} = -\frac{1}{\lambda_{T_{\text{AR}_j}}} \times \ln(r) \quad (4)$$

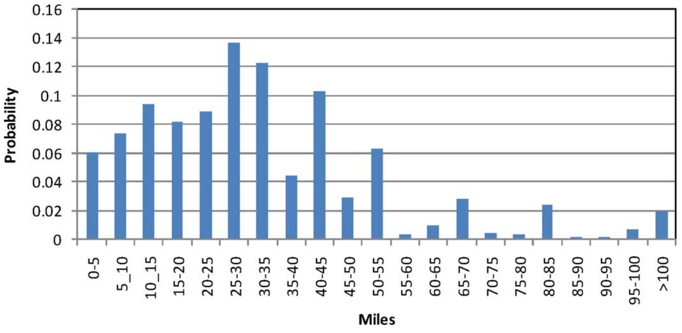

Fig. 4. PDF of distance driven.

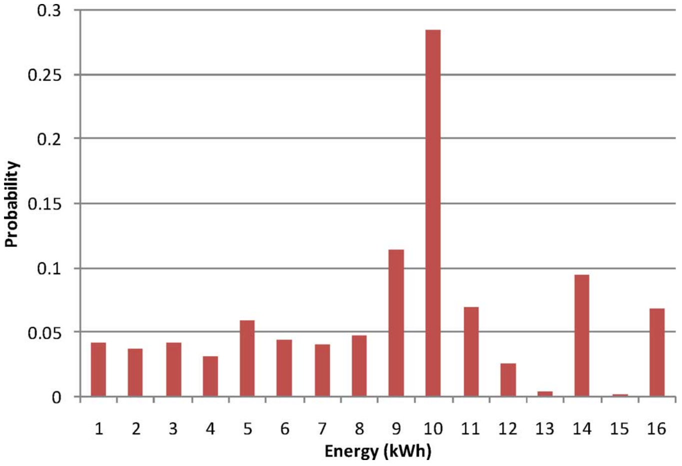

Fig. 5. PDF of energy required for recharging PHEV-30s.

where $\lambda_{T_{\mathrm{AR}j}}$ represents the value of the arrival rate at the arriving time of vehicle j.

3) Charging Duration Time (Service Time): The amount of time that it would take for a PHEV to receive a full charge depends on: 1) its battery capacity; 2) the SOC of its battery upon arrival; and 3) the charging level. Assuming that the battery capacity of the vehicles is designed based on their all-electric range, one can write

$$\mathrm{SOC}_j = \begin{cases} 1 - \left(\frac{d_j}{x_j}\right), & d_j \le x_j \\ 0, & d_j > x_j. \end{cases} \tag{5}$$

Fig. 4 shows the probability distribution for the distance driven according to the 2001 NHTS data. The most probable number of miles driven daily appears to be 30 [24], [40], [41]. Assuming that all vehicles have a 30-mile all-electric range and their battery capacity (BC_j) is as noted in Table II, one can obtain the probability distribution for the energy demand (see Fig. 5). No correlation was found between the arrival time and miles driven by the vehicles in the 2001 NHTS data [42], [43]. The energy required to fully charge vehicle j, and the ERCP and charging duration time (in minutes) of vehicle j are expressed as

$$E_j = (1 - \mathrm{SOC}_j) \times \mathrm{BC}_j. \tag{6}$$

The time duration of the charging process is

$$\tau_j^{\mathrm{ch}} = \frac{E_j}{\mathrm{CL}}. \tag{7}$$

TABLE II
BATTERY CAPACITY FOR FOUR TYPES OF PHEV-30S

Type	BC (kWh)
Compact Sedan	9.765
Mid-size Sedan	10.815
Mid-size SUV	13.125
Full-size SUV	15.225

4) Tolerance Duration: In order to simulate a more realistic customer behavior and include the customers' constraints in the simulation framework, the tolerance duration is considered as one of the inputs to the simulation framework. This input expresses how long the driver is willing to wait before the charging process begins. The tolerance duration also reflects the constraints of the power grid, as a PHEV is allowed to receive a charge as long as the total load does not violate the maximum electricity generation.

The number of vehicles giving up is one of the power grid's performance evaluation parameters. In the most pessimistic case, the tolerance duration is zero, and utility customers expect the charging service to be available upon request. In the most optimistic case, the tolerance duration is unlimited, and users are flexible enough to utilize the charging service even a few hours later. However, this simulation framework considers a normal distribution with a mean of μ and a variance of σ^2 as

$$\tau_j^{\mathrm{tol}} \sim N(\mu, \sigma^2). \tag{8}$$

C. Flowcharts (Workflow)

Upon arriving at the simulation framework, each PHEV is plugged in (begins charging) if there is an idle outlet; otherwise, it must wait in the queue. Once an outlet becomes available, the first vehicle in the queue starts charging. If the wait time for a vehicle exceeds its tolerance duration, it gives up and leaves the queue. Therefore, when charging is complete or the tolerance duration is exhausted, the PHEV leaves the system. Consequently, three events are possible in this simulation framework: the arrival event (AR), the charging-complete event (CC), and the giving-up event (GU).

Figs. 6–8 present flowcharts of the logical procedures in response to AR, CC, and GU events, respectively. The simulation begins at t_0 with the first arrival event, and the subsequent events are programmed during the execution of each flowchart process and recorded in the FEL, finally terminating at t_{end}. The time-step accuracy is one minute. The events on the FEL occur chronologically. Parameters τ^{AR}, τ^{ch}, and τ^{tol} are stochastic values generated by the PDFs of inter-arrival time, charging duration, and tolerance duration, respectively (all already described in Section II-B).

1) Arrival Event : As shown in Fig. 6, when vehicle j arrives at time t, if at least one outlet is available, its charging-start time and charging-complete time are scheduled in the FEL as

$$T_j^{\mathrm{AR}} = T_j^{\mathrm{CS}} = t \tag{9}$$

$$T_j^{\mathrm{CC}} = T_j^{\mathrm{CS}} + \tau_j^{\mathrm{ch}}. \tag{10}$$

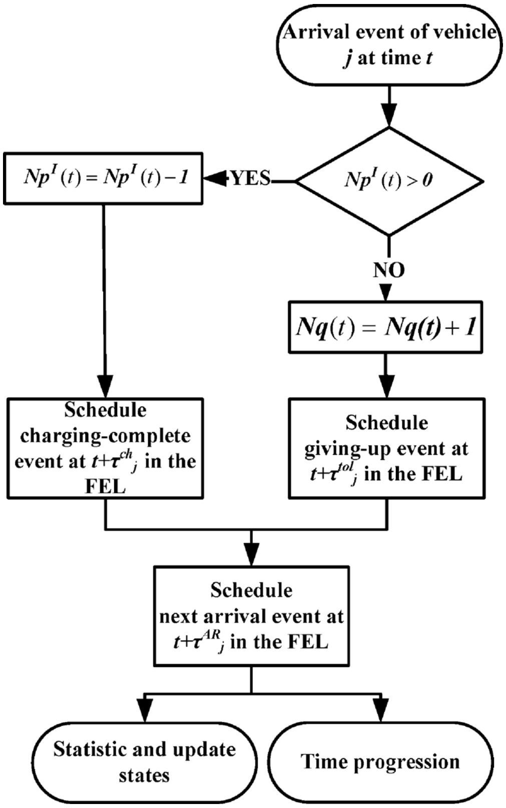

Fig. 6. Flowchart of an arrival event.

Otherwise, the queue length increases by one, and the giving-up event is scheduled in the FEL as

$$T_j^{\mathrm{GU}} = t + \tau_j^{\mathrm{tol}}. \tag{11}$$

Also, the next vehicle's arriving time is programmed as

$$T_{j+1}^{\mathrm{AR}} = T_j^{\mathrm{AR}} + \tau_j^{\mathrm{AR}} \tag{12}$$

when

$$T_0^{\mathrm{AR}} = 0 \tag{13}$$

and the number of PHEVs having arrived before time t is updated as

$$N^{\mathrm{PHEV}}(t) = j. \tag{14}$$

2) Charging-Complete Event: When a charging-complete event occurs, the charging-start time and charging-complete time of any vehicles waiting in the queue are scheduled in the FEL based on (9) and (10). Otherwise, the number of idle outlets increases by 1, as shown in Fig. 7.

3) Giving-Up Event: When the FEL determines that a giving-up event will occur at time t but the PHEV is not plugged in by that time, the queue length will decrease by one. In other words, the vehicle will leave the queue and give up.

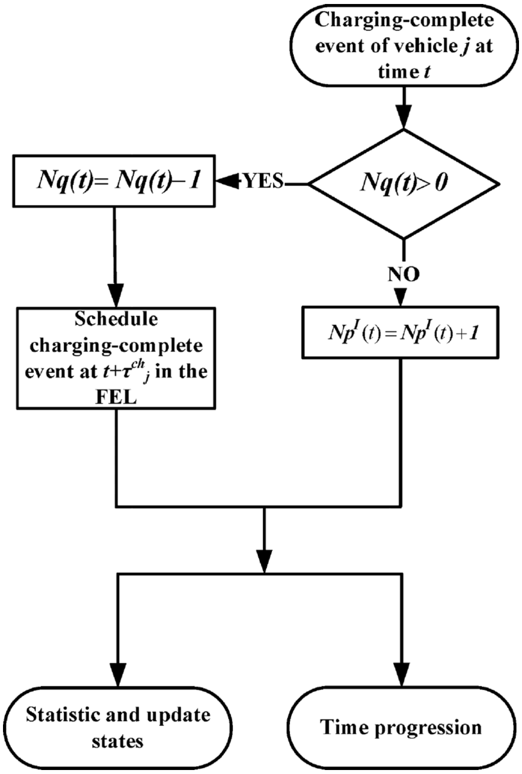

Fig. 7. Flowchart of a charging-complete event.

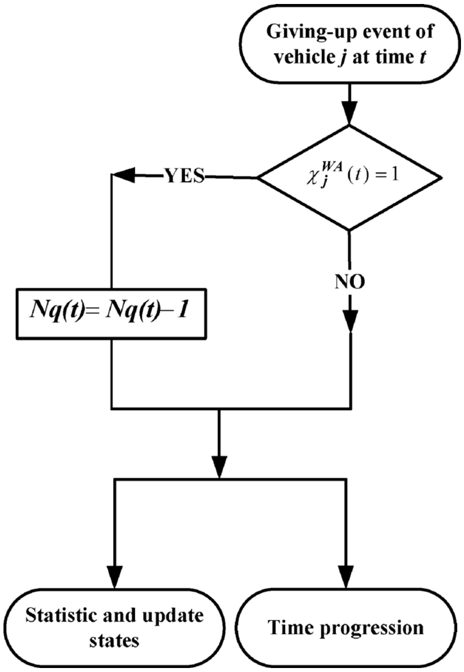

Fig. 8. Flowchart of a giving-up event.

The state variables of vehicle j at time t are the waiting, plugged-in, charging-complete, or giving-up states. They vary by each event occurrence, therefore

$$\chi_j^{\mathrm{WA}}(t) = \begin{cases} 1, & T_j^{\mathrm{AR}} \le t \le \min(T_j^{\mathrm{CS}}, T_j^{\mathrm{GU}}) \\ 0, & \text{otherwise} \end{cases} \tag{15}$$

$$\chi_j^{PI}(t) = \begin{cases} 1, & T_j^{\text{CS}} \le t \le T_j^{\text{CC}} \\ 0, & \text{otherwise} \end{cases} \tag{16}$$

$$\chi_j^{CC}(t) = \begin{cases} 1, & T_j^{\text{CC}} \le t, T_j^{\text{CS}} \ne 0 \\ 0, & \text{otherwise} \end{cases} \tag{17}$$

$$\chi_j^{GU}(t) = \begin{cases} 1, & T_j^{\text{GU}} \le t, T_j^{\text{CS}} = 0 \\ 0, & \text{otherwise} \end{cases}. \tag{18}$$

Each vehicle at each moment must have only one state, so

$$\chi_j^{\text{WA}}(t) + \chi_j^{\text{PI}}(t) + \chi_j^{\text{CC}}(t) + \chi_j^{\text{GU}}(t) = 1. \tag{19}$$

D. Outputs

As shown in Figs. 6–8, during the simulation and at the end of each event, related statistics are collected, and the following outputs are generated. The results are for 24 h, and the time step for the following equations is 1 min.

1) Percentage of Charged PHEVs: The proportion of the total studied vehicles that are charged at the end of the simulation is calculated as

$$\begin{aligned} &\%\text{Charged} \\ &= \left(\frac{1}{N^{\text{PHEV}}(t_{\text{end}})} \sum_{j=1}^{N^{\text{PHEV}}(t_{\text{end}})} \chi_j^{\text{CC}}(t_{\text{end}}) \right) \times 100\%. \end{aligned} \tag{20}$$

2) Percentage of Uncharged PHEVs: The proportion of PHEVs that give up due to the shortage of available power is calculated as

$$\begin{aligned} &\%\text{Uncharged} \\ &= \left(\frac{1}{N^{\text{PHEV}}(t_{\text{end}})} \sum_{j=1}^{N^{\text{PHEV}}(t_{\text{end}})} \chi_j^{\text{GU}}(t_{\text{end}}) \right) \times 100\%. \end{aligned} \tag{21}$$

3) Mean Wait Time: The mean wait time is the time that PHEVs wait in the queue before either receiving a charge or giving up, which is calculated as in (22). A shorter wait time indicates a more promising response of the power system to the charging demand.

$$\begin{aligned} t_w =& \frac{1}{N^{\text{PHEV}}(t_{\text{end}})} \sum_{j=1}^{N_{t_{\text{end}}}^{\text{PHEV}}} (\chi_j^{\text{GU}}(t_{\text{end}}) \times (T_j^{\text{GU}} - T_j^{\text{AR}}) \\ &+ \chi_j^{\text{CC}}(t_{\text{end}}) \times (T_j^{\text{CS}} - T_j^{\text{AR}})). \end{aligned} \tag{22}$$

4) Charging Load Profile: At each time point, the amount of power delivered to the PHEVs depends on the number of busy outlets and the charging level. Therefore

$$Np^B(t) = \sum_{j=1}^{N^{\text{PHEV}}(t)} \chi_j^{\text{PI}}(t) \tag{23}$$

and the charging demand can be calculated as

$$\text{Charging load}(t) = Np^B(t) \times \text{CL}. \tag{24}$$

5) Total Load Profile: The total load profile is calculated as

$$P^T(t) = L(t) + Charging\ load(t). \tag{25}$$

6) Idle Capacity: The capacity of the power grid that is not used, in kilowatt hours, is calculated as

$$C_{\text{Idle}} = \frac{1}{60} \times \sum_{t=t_0}^{t=t_{\text{end}}} (C_{\max} - P^T(t)). \tag{26}$$

7) Unmet Energy: The amount of energy that the power grid could not provide to charge those PHEVs that gave up is calculated as

$$E_{\text{Unmet}} = \sum_{j=1}^{N^{\text{PHEV}}(t_{\text{end}})} (E_j \times \chi_j^{\text{GU}}(t_{\text{end}})). \tag{27}$$

III. APPLICATIONS TO TWO REGIONS IN THE UNITED STATES

The simulation framework can be applied to any region, provided that information is available regarding the power grid's capacity, the domestic load profile, and the number of conventional vehicles. Here, we apply the proposed simulation framework to two North American Electric Reliability Corporation (NERC) regions. The summer load is higher than the winter load in both regions; the average summer domestic load profile serves as the basis of the study. The simulation framework runs for three days with an accuracy of 1 min, and the results are shown for the second day. The simulation assumes that most drivers can tolerate, on average, a 1-h delay; hence, the tolerance duration follows a normal distribution with a mean of 1 h and a standard deviation of 15 min or $N(60,\ 15^2)$. The charging levels used in this study are 1.4 and 7.68 kW. Also, the grid capacities are assumed to be 5% over the maximum domestic loads.

A. East Central Area Reliability Coordinating Agreement (ECAR)

The simulation runs for 27.7 million vehicles (the region's total number of conventional vehicles [11]), and the grid capacity limitation is assumed to be 90 000 MW. Figs. 9 and 10 show the PHEV charging load profiles with 1.4- and 7.68-kW charging levels, respectively. The dotted curves represent the case when there is no limitation, that is, all PHEVs are plugged in (begin charging) upon arrival regardless of the grid's capacity. The solid lines represent the case when the limitations of the grid are applied. These figures indicate the extent of load profile deformation due to grid limitations at 100% penetration. According to the figures, a higher charging level causes larger deformation. Figs. 11 and 12 show the resulting total load profiles when the simulation runs at 33%, 66%, and 100% PHEV penetration rates with 1.4- and 7.68-kW charging levels, respectively. In these two figures, the PHEV charging load profile has been added to the domestic load profile to obtain the total load profile. In case of 33% penetration, the total load profile is not

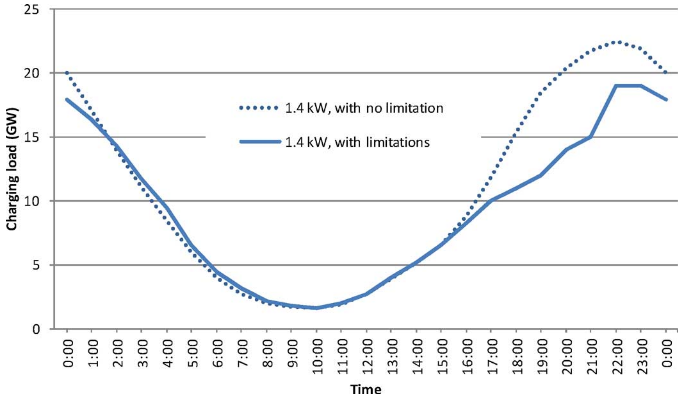

Fig. 9. PHEV charging load profiles at a charging level of 1.4 kW and 100% penetration for ECAR.

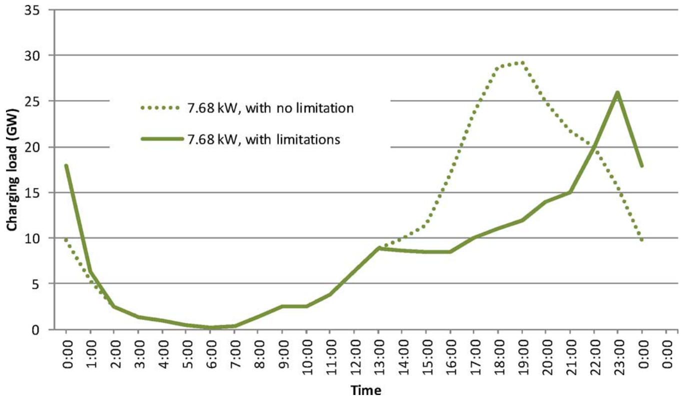

Fig. 10. PHEV charging load profiles at a charging level of 7.68 kW at 100% penetration for ECAR.

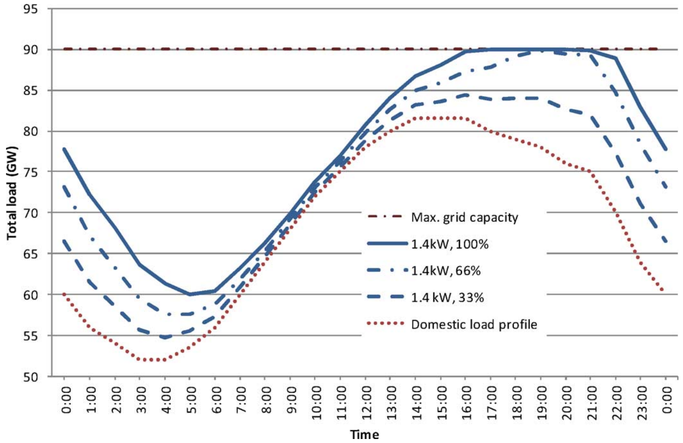

Fig. 11. Domestic and total load profiles at a charging level of 1.4 kW and three penetration levels for ECAR.

cut off. This indicates that all vehicles can receive charge. However, in case of 66% penetration, there is a cut off but not as wide as the 100% penetration case. Similar to deformations, the cutoffs at the 7.68-kW charging level are wider than those at the 1.4-kW level.

Table III compares the quantitative values for 1.4- and 7.68-kW charging levels, indicating that the existing power system can meet the charging demand of at least 76% of PHEVs. However, PHEVs must wait an average of 30–45 min before receiving any charge. This table also shows that the results at a 1.4-kW charging level are better than those of a 7.68-kW charging level. At the lower charging level, a smaller percentage of vehicles will be denied service; also, the wait time is shorter. In addition, the unmet energy is half of that of the higher charging level. According to Table III and (26), after adding the PHEV charging load to the domestic load, still the grid has a large idle capacity compared with the unmet energy in both charging levels. Therefore, applying a charging policy (controlled charging) in this region will be very effective in minimizing or even eliminating the unmet energy.

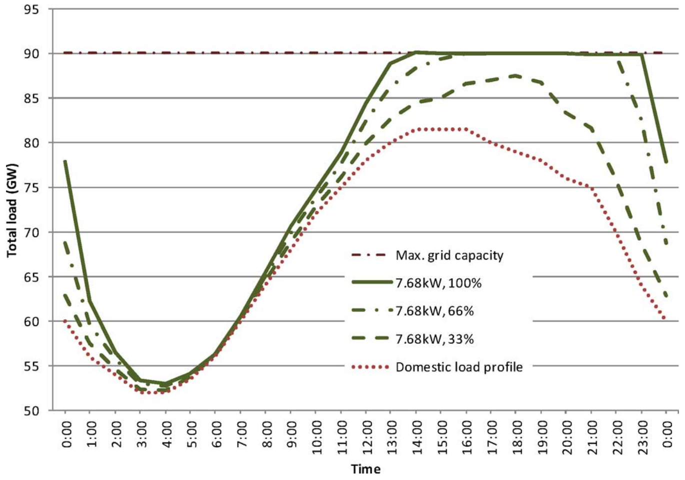

Fig. 12. Domestic and total load profiles at a charging level of 7.68 kW and three penetration levels for ECAR.

TABLE III

COMPARISON OF PERFORMANCE PARAMETERS FOR TWO CHARGING LEVELS FOR ECAR WITH 100% PENETRATION

Performance Parameters	Level 1 (1.4 kW)	Level 2 (7.68 kW)
% Charged	88%	76%
% Uncharged	12%	24%
Mean wait time in the queue (minutes)	30	45
Idle capacity (MWh)	295,422	324,453
Unmet energy (MWh)	31,620	59,937

B. California and Southern Nevada (CNV)

In this region, there are 25.8 million vehicles [11]. The maximum power grid capacity is assumed to be 40 000 MW. Similar to the previous region, Figs. 13 and 14 show the deformations of PHEV charging load profiles at charging levels of 1.4 and 7.68 kW, respectively. As these figures indicate, the load profile deformations are more severe in this region than in the ECAR region. Also, Figs. 15 and 16 represent the resulting total load profiles at two charging and three penetration levels. In this region, even for a 33% PHEV penetration level, the power grid cannot meet the charging demand.

Table IV includes the quantitative values, indicating the fact that the power grid of this region can only meet 39% of the demand of PHEVs at best. Also, similar to ECAR, the results produced at a 1.4-kW charging level are better than those produced at a 7.68-kW charging level. For example, both idle capacity and unmet energy at the 1.4-kW charging level are lower than those of the 7.68-kW charging level. However, compared with

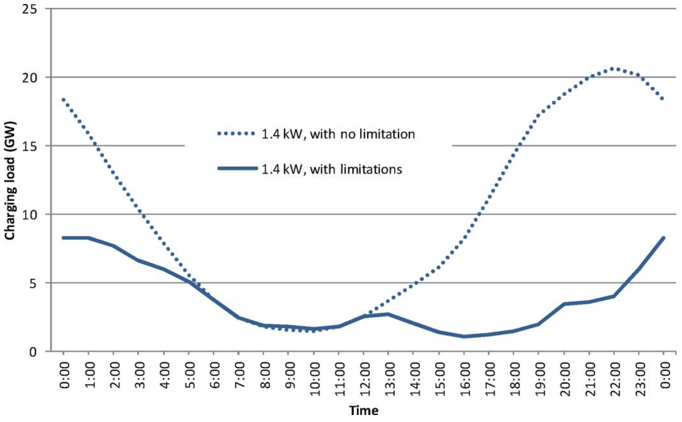

Fig. 13. PHEV charging load profiles at a charging level of 1.4 kW and 100% penetration for CNV.

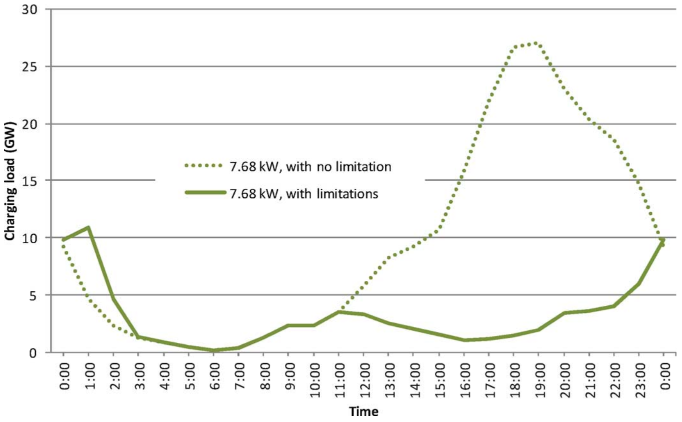

Fig. 14. PHEV charging load profiles at a charging level of 7.68 kW and 100% penetration for CNV.

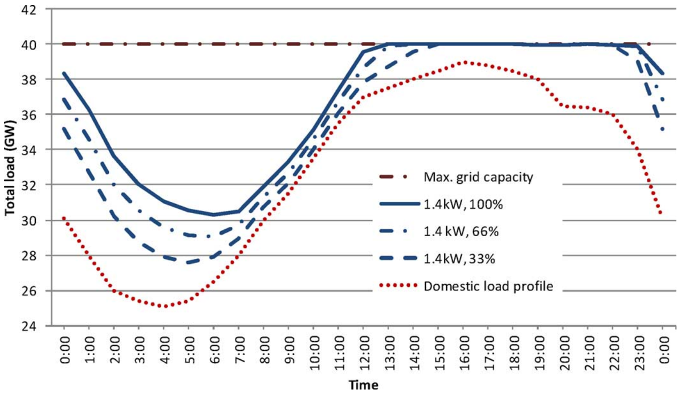

Fig. 15. Domestic and total load profiles at a charging level of 1.4 kW and three penetration levels for CNV.

the ECAR region, drivers in this region have to wait longer before receiving any charge. In addition, despite the ECAR region, here the idle capacity is less than the unmet energy at both charging levels. This indicates that, even by applying a controlled charging policy; the power grid would not be able to meet the charging demand. Also, comparing the above figures based on the charging levels in both regions shows that a higher charging level causes a wider and larger peak, similar to [39], which showed that the peak becomes displaced and varied by different charging levels.

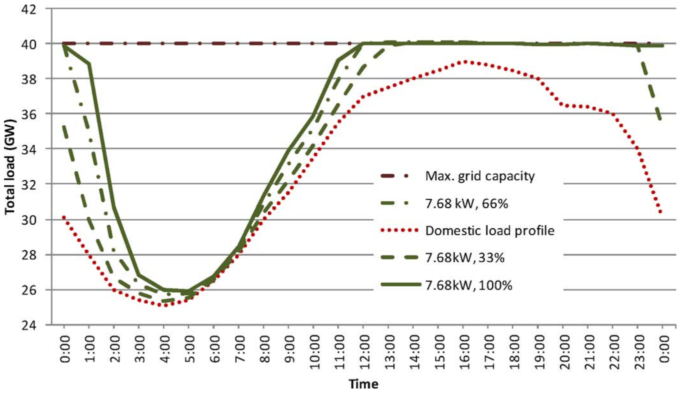

Fig. 16. Domestic and total load profiles at a charging level of 7.68 kW and three penetration levels for CNV.

TABLE IV

COMPARISON OF PERFORMANCE PARAMETERS FOR TWO CHARGING LEVELS FOR CNV WITH 100% PENETRATION

Performance Parameters	Level 1 (1.4 kW)	Level 2(7.68 kW)
% Charged	39%	28%
% Uncharged	61%	72%
Mean wait time (minutes)	57	65
Idle capacity (MWh)	81,922	96,930
Unmet energy (MWh)	141,545	167,648

IV. CONCLUSION

A simulation framework has been proposed for examining the power system's ability to meet the charging demand of PHEVs. It sets the power system's limitation so that the total load profile never surpasses the power grid's limits during the simulation. It simulates the customers' charging request behaviors and evaluates the response of the power system to the charging demands through the output load profiles and values. Output parameters, which consist of both quantitative and qualitative values, indicate how readily and efficiently the power system supplies the extra demands due to the PHEV charging load from the customers' perspectives.

Results for the two NERC regions studied by the simulation framework indicate that the power system's ability to supply the charging demand is different for each region. This ability strongly depends on the region's population and grid capacity. Hence, the power grid of the first region meets 76% of the charging demand, while that of the second region supplies only 28% of the PHEVs' demand. Therefore, in some areas, the existing power system is better prepared to meet the charging demand even in the case of high penetration levels. However, in other areas, it is necessary to extend the existing power system or to apply strict policies even in the case of low penetration levels.

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