Impact of Available Electric Vehicle Battery Power Capacity on Power System Reliability

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Abstract—**This paper focuses on estimating the available power capacity that electrical vehicles (EVs) can provide for the reserve market and evaluating its impact on power system reliability. The proposed approach estimates the available power capacity in a probabilistic manner based on traffic conditions through Markov process, which takes into account time durations when EVs are scheduled to provide the reserve services, the battery charge depletion limit and the energy needed for transportation purposes. A method to evaluate the reliability of the combined system (conventional system plus EVs) based on the probabilistic model is presented. Finally, numerical experiments are conducted to validate the effectiveness of the proposed approach and show significant impact of EVs on system's reliability through the ancillary service market.**

***Index Terms*—electricity supply industry deregulation; electric vehicles; power system reliability**

I. INTRODUCTION

With the price of oil rapidly peaking in the past and the threat of global climate change increasingly acknowledged, Electric Vehicles (EVs) are expected to become the economic and environmental friendly choice for transportation. Since point source (smoke stack) pollution is easier to control than mobile (tail-pipe) source pollution, the wide adoption of EVs can greatly help reduce the carbon emission and hence alleviate the environmental challenges [1].

Nowadays more and more attention has been paid to EVs due to the introduction of the Vehicle -to- Grid(V2G) concept, which means EVs can discharge the energy to an electric power grid during the parking hours [2]. This idea enables EVs to provide energy to the grid when needed and hence become potential participants in electricity market. In [3] the authors analyze four electricity markets' incentives to purchase V2G power, and point out that V2G can be competitive in ancillary service markets of spinning reserves and regulation. It is quite impossible for hundreds of thousands of PHEVs to participate in the electricity market by themselves, and [4] points out that an intermediate service provider, called "*aggregator*", is necessary to manage the small-scale power of vehicles to provide the ancillary service at the appropriate large-scale power system level.

For the sake of properly bidding into the ancillary market, aggregators must know how much energy in EVs is available across their service area footprint. In [3] the authors propose a method to calculate the power capacity value of electric vehicles considering time duration and some hardware limitations. This approach, however, fails to take into account the availability of electric vehicles. Recently, some researchers have investigated this problem and proposed ways to simulate the availability of EVs and calculate the available power capacity from EVs. In [5-8], stochastic models which are based on Monte Carlo, Fuzzy VPRS Model, and non-homogeneous semi-Markov processes are proposed to estimate the availability of EVs in the system considering drivers' behavior. In [9], a mathematical model for estimating the electric power capacity of a parking lot is described. Authors in [4] proposed the analytical way to derive the probability distribution of available power capacity of EVs taking into account drivers' plug-in probability.

In this paper, a method to estimate the available power that can be provided by EVs based on data describing traffic condition, which are more accessible and can be monitored in real-time is proposed. The proposed method considers available energy from EVs in parking lots as well as in other places (house garage, etc.) where charging services are provided. The available power capacity that EVs can provide for the reserve market is estimated, and the impact on power system reliability is investigated.

The paper is organized as follows: Section II describes the assumptions that the proposed method is based on. Section III proposes the model for estimating the available power provided by EVs. Section IV presents the approach to evaluating EVs' reliability impacts on the power system. Section V illustrates the Unit Commitment model used in this paper to clear the ancillary services market. In section VI numerical experiments are presented and the results are analyzed. At the end, section VII gives conclusions.

II. BASIC ASSUMPTIONS

A. V2G Operating Mode Is Allowed

Although the feasibility of EVs' operating in V2G mode is argued a lot, as discussed in [10] , but we still assume in this paper that EVs are allowed to provide energy back to the grid in a V2G mode predicting that this mode of operation may be acceptable 10-20 years down the road.

B. Accessibility to Charing Services Is Guaranteed

As an outcome of widespread adoption of EVs, the development of (dis)charging infrastructure will guarantee the accessibility to (dis)charging services. It is assumed that, electric vehicles parked in the parking lot, house garage, and etc. have the accessibility to such (dis)charging services.

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C. The Total Number of EVs is Constant

Although the number of EVs travelling on the roads varies during the day and so does the number of EVs parked and connected to the grid, we assume that the sum of them, namely, total number of EVs, in a large area is constant.

III. Modeling Process

A. The Estimation of Availability of EVs

In order to estimate the number of EVs traveling on the road, we use a homogeneous Markov model with exponentially distributed inter-arrival and driving time. The flow of vehicles coming into the traffic is therefore assumed to be a Poisson process [11]. Figure 1 presents the Markov chain describing the number of vehicles on the roads in the traffic system. In Figure 1, λ is the incoming rate of the vehicles into the traffic system, μ is the departure rate of the vehicles off the traffic system, m is the maximum capacity of the traffic system, and we assume that vehicles won't come into the traffic system when the system has achieved its full capacity.

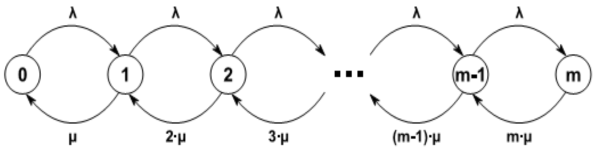

Figure 1. Markov Chain Describing the State of Traffic System [11]

Then, the state-transition matrix can be expressed in (1).

$$A=\begin{pmatrix} -\lambda & \lambda & & & \\ \mu & -(\lambda+\mu) & \lambda & & \\ & 2\mu & -(\lambda+2\mu) & \lambda & \\ & \ddots & \ddots & \ddots & \\ & & (m-1)\mu & -(\lambda+(m-1)\mu) & \lambda \\ & & & m\mu & -m\mu \end{pmatrix} \tag{1}$$

The probability of the traffic system having k vehicles at time t is notated as $P_k(t)$, and the vector $\mathbf{P}(t)=\left(P_0(t) \quad P_1(t) \quad \cdots \quad P_m(t)\right)^T$. According to Markov process, we can get (2)

$$\mathbf{P}(t)'=\mathbf{P}(t)A \tag{2}$$

If transition state is not considered, then (3) and (4) can be obtained.

$$0=\mathbf{P}A \tag{3}$$

$$\sum_{i=0}^{m} P_i = 1 \tag{4}$$

If we combine (3) and (4), the result will be as follows.

$$P_k=\frac{\rho^k}{k!}P_0 \qquad k=1,2,\cdots m \tag{5}$$

$$P_0=\left(\sum_{i=0}^{m}\frac{\rho^i}{i!}\right)^{-1} \qquad \rho=\frac{\lambda}{\mu} \tag{6}$$

When the traffic system can hold a huge number of vehicles, which means $m\to\infty$, then equation (7) is yielded.

$$\lim_{m\to\infty} P_0 = e^{-\rho} \tag{7}$$

Substituting equation (7) to (5), we can obtain equation (8).

$$P_k=\frac{\rho^k}{k!}e^{-\rho} \quad \rho=\frac{\lambda}{u} \quad k=1,2,\cdots m \tag{8}$$

This means that when traffic system is spacious enough to hold large number of vehicles, and the probability that there are k vehicles travelling on the roads behave like a Poisson distribution. If we assume that the total of EVs in the large area is N, then the probability that there are j EVs parked and connected to the grid can be shown as:

$$P_j^{in}=\frac{\rho^{(N-j)}}{(N-j)!}e^{-\rho} \quad j=1,2,\cdots m \tag{9}$$

As well known, traffic conditions vary from time to time; however, here we assume that traffic conditions do not vary too much in one unit of time, for example one hour. Then according to hourly incoming and departing rates, we can get estimation of availability of EVs in different hours during one day [12].

B. Estimation of the Available Energy from EVs

Besides the availability of the EVs to the grid, the energy every vehicle holds should be obtained in order to estimate the available energy that EVs can provide to the grid. In this paper, we assume that the energy E in an EV is a variable in a normal distribution, which means $E \sim N(\omega, \sigma^2)$. Note that the parameters ω *and* σ vary in one day; ω will be higher at night, while σ will be lower at night because most EVs will be charging at night compared with the day case.

Based on the assumption regarding battery energy mentioned above, the cumulative distribution of the energy that EVs can provide to the grid at one moment can be obtained through (10).

$$F_Z(z)=\int_{-\infty}^{z}\sum_{j=1}^{m}\frac{\rho^{(N-j)}}{(N-j)!}e^{-\rho}\frac{1}{j\sqrt{2\pi}\sigma}e^{-\frac{(\frac{u}{j}-\omega)^2}{2\sigma^2}}du \tag{10}$$

Then the probability density of energy that EVs can provide to the grid is shown in (11):

$$f_Z(z)=\sum_{j=1}^{m}\frac{\rho^{(N-j)}}{(N-j)!}e^{-\rho}\frac{1}{j\sqrt{2\pi}\sigma}e^{-\frac{(\frac{u}{j}-\omega)^2}{2\sigma^2}} \tag{11}$$

C. Estimation of the Available Power from EVs

The power is determined by two aspects: energy and time duration. The probability distribution of available energy can be obtained through (10), and we regard $F^{-1}{}_Z(0.05)$ as the exact amount of energy that can be provided by EVs, which means that the probability that EVs can provide energy no less than that amount will be 95%. If we suppose the time duration is h, then the power from EVs can be obtained through (12).

$$power=\frac{F^{-1}{}_Z(0.05)}{h} \tag{12}$$

Technically, batteries shouldn't be depleted below 20%. If we suppose that the total battery capacity of EVs in one large area is C_{to}, then the available power can be shown in (13).

$$power_{-20\%} = \frac{F^{-1}{}_Z(0.05)\text{-}0.2\times C_{to}\times\frac{N-\rho}{N}}{h} \quad (13)$$

Moreover, if we take into account the vehicles are about to start their travel and make sure that they can have enough energy to get to their destination without violating the 20% depletion rate, and suppose that every vehicle will need q energy on average to finish their travel, then the available power can be estimated by using (14).

$$power_{-20\%\text{-leave}} = \frac{F^{-1}{}_Z(0.05)\text{-}0.2\times C_{to}\times\frac{N-\rho}{N} - q\times\rho}{h} \quad (14)$$

IV. EVS' RELIABILITY IMPACT ON POWER GRID

Compared with the generators, EVs can be regarded as unconventional energy sources. In order to evaluate their combined impact on the power system, we can first get the generation system representation of conventional energy sources by using recursive model [13]. Note that the ORR (Outage Replacement Rate)[14] of each unit instead of the FOR (Forced Outage Rate) should be used in order to construct the capacity outage probability table. The peak load in a particular hour is notated as L_p, the total operating capacity of the conventional system which consists of generators is supposed to be C_{gen}, and the probability of the conventional system having x MW capacity loss is denoted as $p(x)$. Then we can get the Loss of Load Probability (*LOLP*) of the combined system as follows:

$$LOLP = \sum_{0}^{L_p} F_Z(x)\, p(C_{gen}-x) \quad (15)$$

V. EVS' PARTICIPATION IN RESERVE MARKET

According to [3], EVs' available energy can be utilized in ancillary service markets of spinning reserves and regulation. In this paper, EVs' available energy is assigned to participate in reserve market through V2G mode of operation. Authors in [15, 16] provide some conceptual framework for EVs' impact on electricity market. In [4, 17, 18], EVs' participation into reserve market is described and the drivers' behavior is taken into account when EVs' availability such as plug-in probability, travel mode, etc is estimated. In [19, 20], EVs are scheduled to provide frequency regulation service considering the uncertainty brought by EVs availability which is gained through Monte Carlo simulation. Authors in [21] introduce the game theory to determine EVs' participation into the ancillary service market.

In my work, EV aggregators may bid into the reserve market considering the uncertainty brought by EVs, and traffic condition data are used to estimate the available power from EVs. Unlike conventional generators, EVs cannot provide long-term sustainable power, and therefore they are not quite suitable to participate in the day-ahead reserve market. But, they can still bid into the hour-ahead reserve market. And if they still have enough energy left at the end of one hour, they can bid into the market in the next period.

Nowadays, the reserve market and energy market tend to be cleared in one optimization process, and reserve market is cleared through unit commitment. The unit commitment model [22] in this paper is formulated as follows.

$$\min: f = \sum_{i\in G}\sum_{t=t_0}^{T} C_{Gi}p_{Gi}^t + C_{RSi}p_{RSi}^t + C_{EV}p_{EV}^t + C_{Ui}s_{Ui}^t + C_{Di}s_{Di}^t \quad (16)$$

Where C_{Gi} and C_{RSi} are the generation cost and reserve cost of generator i; P^t_{Gi} and P^t_{RSi} are the output of generator i in energy market and reserve market at time period t; C_{EV} is the reserve cost of EVs; P^t_{EV} is the EV's power output in a reserve market; C_{Ui} and C_{Di} are the starting up and shutting down cost; S^t_{Ui} and S^t_{Di} are the starting up and shutting down indicators of generator i at time t.

In [2], Vehicle-to-Building (V2B) option is proposed, which means EVs can provide power back to building connected to the distribution system. Note that P^t_{EV} here can include the power from EVs operating in both V2G mode and V2B mode.

This objective is subject to security constraints, one of which is the balance of supply and demand:

$$\sum_{i\in G} p_{Gi}^t = P_L^t, t = 1, 2, \cdots, T \quad (17)$$

P^t_L is the demand in time t. Meanwhile, the reserve needs should also be met.

$$\sum_{i\in G} p_{RSi}^t + p_{EVi} \geq D_{RS}^t, t = 1, 2, \cdots, T \quad (18)$$

D^t_{RS} is the reserve demand in time t. The following three are about the generation limit of generators.

$$P_{Gi}^t + P_{RSi}^t \leq x_{Gi}^t P_{Gi}^{\max}, i\in G, t = 1, 2, \cdots, T \quad (19)$$

$$x_{Gi}^t P_{Gi}^{\min} \leq P_{Gi}^t \leq x_{Gi}^t P_{Gi}^{\max}, i\in G, t = 1, 2, \cdots, T \quad (20)$$

$$0 \leq P_{RSi}^t \leq P_{Gi}^{\max}, i\in G, t = 1, 2, \cdots, T \quad (21)$$

$P^{min}{}_{Gi}$ and $P^{max}{}_{Gi}$ are the generation limit of generator i, and $x^t{}_{Gi}$ indicates the state of the generator i at time t. Besides, EVs also have some power limit.

$$0 \leq p_{EV}^t \leq P_{EVbid}^t, t = 1, 2, \cdots, T \quad (22)$$

P^t_{EVbid} means the amount that aggregators bid into the market at time t. Moreover, the following constraints should also be met

$$x_{Gi}^t - x_{Gi}^{t-1} \leq s_{Ui}^t, i\in G, t = 1, 2, \cdots, T \quad (23)$$

$$x_{Gi}^{t-1} - x_{Gi}^t \leq s_{Di}^t, i\in G, t = 1, 2, \cdots, T \quad (24)$$

$$x_{Gi}^t, s_{Ui}^t, s_{Di}^t \in \{0,1\}, i\in G, t = 1, 2, \cdots, T \quad (25)$$

During this unit commitment model, line transmission capacity is not considered, because this is not our main focus.

VI. NUMERICAL EXPERIMENTS AND ANALYSIS

We assumed there is an area with approximately 30,000 EVs in total, a half of which are Nissan Leafs of which the battery size is 24 kwh and the other half are Chevy Volts of which the battery size is 16 kwh. According to [23], their average Daily Vehicle Trips is 3.02 times, and Daily Vehicle Miles Traveled (VMT) is 28.97 miles on average. If we assume that the average speed of a vehicle is 40 miles per hour, then the average time period for a vehicle to finish its journey will be about 14 min [(28.97/3.02/40)*60], where 28.97 is the average miles every vehicle travels a day and 3.02 is the average travel frequency. This means that the average departure rate of an EV will be about 4 times per hour. Based on the distribution of vehicle trips by start time investigated in [23] and assumption that the time duration is 1 hour, on average, every EV will need 0.35kw to travel one mile which means q in the formula (14) will be about 3.36kw. The probability density of energy that EVs can provide to the grid during the two different time periods is shown in Figure 2 and Figure 3 respectively.

The power that EVs can provide to the grid in two time periods by using equations (12)-(14) is shown in Table 1, and the estimated available power from EVs in 24 hours is shown in Figure 4.

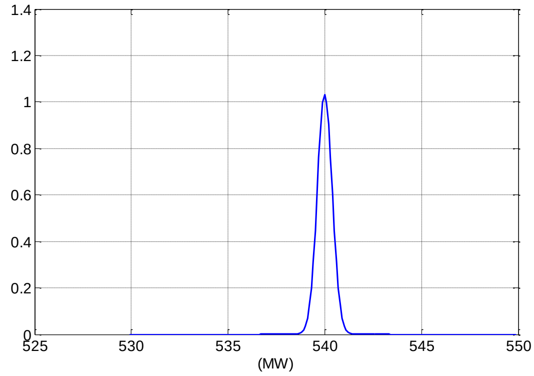

Figure 2. Probability Density of EVs Energy during 3:00 – 4:00 am

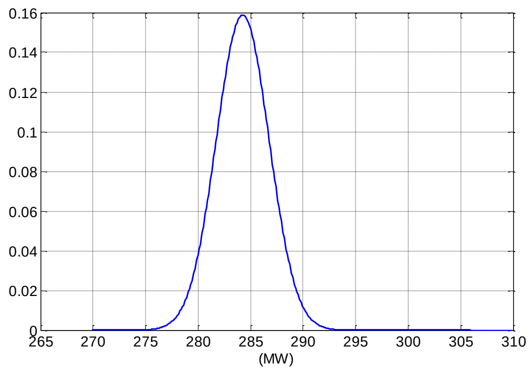

Figure 3. Probability Density of EVs Energy during 4:00 –5:00 pm

From the probability density of EV energy, we can see that EV's available energy behaves quite like a normal distribution which has a relatively low standard deviation especially when it comes to the time interval of 3:00 – 4:00 am. This suggests that by aggregating large number of EVs together the uncertainty in their availability decreases and this is a good characteristic for the widespread adoption of V2G energy. From the results in Table 1 and in Figure 4, we can observe that power which can be provided to the grid will be greatly reduced when the 20% energy depletion limitation is taken into account. However, we can bear the hope that this technical issue can be gradually overcome in the future, thus leading to the increase of available energy from EVs.

TABLE I. THE ESTIMATION OF EV POWER CAPACITY IN TWO TIME PERIODS

Time period	**Power Calculated with Different Considerations**		
	Power (MW)	***Power$_{-20\%}$ (MW)***	***Power$_{-20\%\text{-leave}}$ (MW)***
3:00 – 4:00 am	539.36	419.53	419.39
4:00 – 5:00 pm	280.10	167.59	161.30

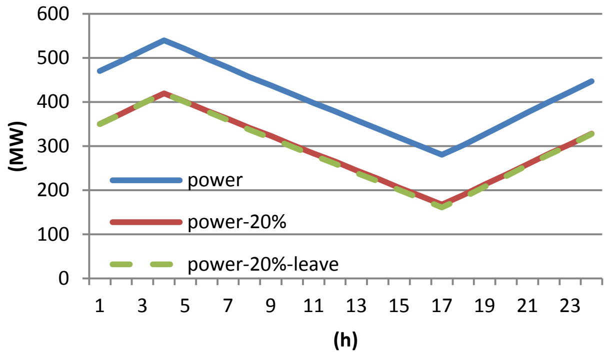

Figure 4. Estimated Available Power during 24 Hours

Let's assume that transmission line transfer capability is neglected, and electric vehicles in that area are all aggregated to participate into the reserve market when they are parked and connected to the grid. The aggregator decides to participate into the reserve market while considering the 20% depletion limit of batteries in the next hour which is 4-5 pm. Then a 24-hour Unit Commitment starting from that hour should be done in order to clear the market. Here we use a modified IEEE-RTS 96 test case [24]. The result of online capacity of conventional generation system calculated after the unit commitment with and without EVs' participation and hourly peak load can be illustrated in Figure 5. Note that the hour 17 will be the first hour in the calculation of Unit Commitment. From Figure 5, we can see that because of the participation of EVs, some generators can be turned off, especially when the system load is relatively high.

In order to obtain the reliability impact of EVs on power system, LOLP is calculated according to the results of Unit Commitment in three scenarios: 1) there is no existing EV or EVs cannot provide energy to the grid; 2) EVs can be a source of energy but they do not participate into the ancillary service market; 3) EVs participate into the ancillary service market considering the 20% depletion limit. The result of LOLP can be shown in Figure 6.

From Figure 6, we can see that the whole system's reliability will be greatly improved if EVs are enabled to provide energy back to grid. Moreover, in scenario 2, the whole system has the lowest LOLP, and this is because: 1) there is a relatively high online capacity of generators; 2) EVs, although not bidding into the electricity market, can still operate as a reserve when badly needed due to their high ramping rate. As can be observed from the figure, EV's participating into reserve market also does contribute to system's reliability.

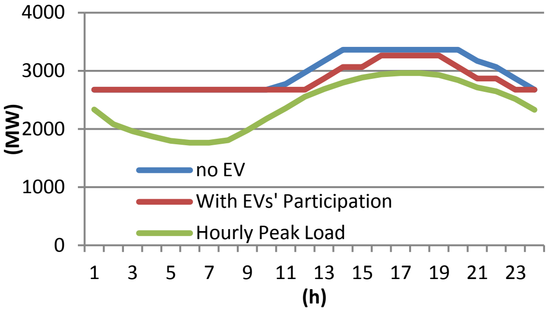

Figure 5. Online Cpacity with and without EVs and Hourly Peak Load

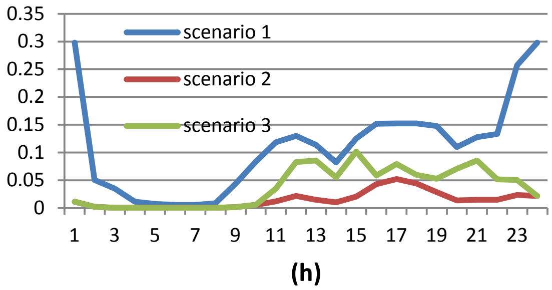

Figure 6. Illustration of Hourly LOLP in Three Scenarios

VII. CONCLUSIONS

From the result, we can see that:

- EVs' available energy behaves quite like a normal distribution with a relatively low standard deviation, and the limits caused by battery greatly decrease the power that EVs can provide.
- Participation of EVs will contribute to system's reliability as witnessed by LOLP results shown in the Figure 6.

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