Impact on Power System Flexibility by Electric Vehicle Participation in Ramp Market

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***Abstract*—This paper investigates electric vehicle (EV) participation in the flexible ramp market. We take into account EV stochastic mobility, and evaluate impact on power system reliability and flexibility. Based on dynamic programming, the model deals with uncertainties and variations of net load, as well as EV charging requirements. Markov process is utilized in estimating the aggregated power capacity of EVs. Two participation modes are analyzed: 1) EV direct provision of the ramp product; and 2) EV cooperation with the conventional generator. Moreover, we propose new indices to evaluate power system flexibility. Finally, numerical experiments are conducted to validate the proposed approach and illustrate how EV involvement into the ramp market can improve power system reliability and flexibility.**

***Index Terms*—Electric vehicles (EVs), flexibility, ramp market, reliability.**

NOMENCLATURE

λ	Vehicles' arrival rate into the traffic system.
μ	Reciprocal of the mean travel time.
m	Maximum capacity of the traffic system.
γ_{ij}	Transition rate from states i to j of the Markov model.
E_{sij+}	Discharging energy per electric vehicle (EV) under states i or j.
ω_{sij+}	Mean discharging energy per EV under states i or j.
σ_{sij+}	Standard deviation of the discharging energy per EV under states i or j.
$F_{Z+}(z)$	Cumulative distribution of EV available discharging energy.
$f_{Z+}(z)$	Probability density function of EV aggregated discharging energy.
C_{EVtotal}	EV total battery capacity in one large area.
q	Average energy per EV to finish the travel.
Energy^{+}	EV aggregated energy capacity for discharging.
Energy^{-}	EV aggregated energy capacity for charging.
h	Time duration of EV charging/discharging.
Power^{+}	EV aggregated discharging power.
$r_{\max}^{+}$	Maximum discharging rate for one EV.
$p_{\text{EV}+}^{\max}$	EV aggregated discharging power capacity.
$p_{\text{EVG}+}$	EV discharging power in the market.
$p_{\text{EVG}-}$	EV charging power in the market.
FRU_{EV}	EV ramp up service in the market.
FRD_{EV}	EV ramp down service in the market.
G	Set of the on-line generators.
p_{Gi}^{t}	Generation output of generator i at time t.
FRU_{i}^{t}	Ramp up service of generator i at time t.
FRD_{i}^{t}	Ramp down service of generator i at time t.
$C_{\text{FRU}i}$	Cost of the ramp up service for generator i.
$C_{\text{FRD}i}$	Cost of the ramp down service for generator i.
C_{EVG}	Cost for EVs to provide the energy service.
C_{EVFRU}	Cost for EVs to provide the ramp up service.
C_{EVFRD}	Cost for EVs to provide the ramp down service.
P_{L}^{t}	Net load at time t.
$p_{\text{EVG}-}^{t}$	EV charging load at time interval t.
$p_{Gi}^{\min}$	Minimum generation of the generator i.
$p_{Gi}^{\max}$	Maximum generation of the generator i.
R_{i}	Ramp rate of the generator i.
Δt	Time interval period to ramp up or down.
D_{FRU}^{t}	System requirement for ramping up at time t.
D_{FRD}^{t}	System requirement for ramping down at time t.
E_{EV}^{t}	EV aggregated energy at time t.
η^{+}	EV discharging coefficient.
η^{-}	EV charging coefficient.
C_{req}	EV energy requirement.

I. INTRODUCTION

THE FLEXIBILITY issue has drawn increasing attention ever since the growing penetration of renewable energy sources aiming at reducing power systems' carbon emission. Though being clean and relatively inexpensive, renewable energy sources are making it quite challenging to predict or control their outputs. Integration of renewable energy demands improving power system flexibility, since its variability can lead to difficulties in energy balancing, thus compromising the power system operation efficiency and reliability [1], [2].

Nowadays, a new market product, the flexible ramping product, has been recently proposed by different independent system operators (ISOs) to accommodate net load variations and uncertainties [3]–[5]. The objective of this product is to build dispatch flexibility in terms of ramp capability in real-time dispatch (RTD) to meet energy imbalances that may arise in the future.

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There are many valuable studies of the flexible ramping product. References [6]–[9] discuss the impact of the flexible ramping product on operation as well as power system reliability and flexibility. Congcong *et al.* [10] proposed a new principle to determine the amount of ramp capacity needed. Thatte *et al.* [11] and Wang and Hobbs [12] compared the performances of the flexible ramping product model, traditional dispatch model, stochastic model, and robust model. However, few efforts have been devoted to discuss EV provision of the flexible ramping product.

A. *Related Work*

EVs have become more and more popular, not only because of their capability to decrease carbon emission in transportation [13], but also of their potentials to improve power system reliability and flexibility. EVs can be quite adjustable in different operation modes: 1) grid-to-vehicle (G2V); 2) vehicle-to-grid (V2G); and 3) vehicle-to-building (V2B) [14], and they have been suggested to participate in the electricity market by providing ancillary services such as reserve and regulation in a lot of studies, such as [15]–[24]. However, the constraints on EV battery capacity and battery cost related to frequent charging/discharging are the core problems restricting EV flexible performance in the electricity market.

Different from the operating reserve, the ramp product can be integrated in RTD, which is applied on a 5–10 min time scale, and therefore the limitation caused by EV battery capacity can be relieved. Moreover, the ramp capacity is usually dispatched in just several short intervals due to the infrequent appearance of large variations. EVs, if participating, will not have to charge or discharge frequently, compared with the frequency regulation, while their fast ramping capability can still be rewarded. What is more important is that by bidding into the ramp market, EVs can more effectively improve the ISOs dispatch flexibility in RTD compared with their involvement in reserve or regulation. This is due to the fact that the ramp product can be dispatched in RTD on a regular basis, whereas regulations are dispatched by automatic generation controls and operating reserves only after major contingency happens.

B. *Framework of this Paper*

This paper aims at investigating EV possible participation in the ramp market and their corresponding impact from system operators' point of view considering EV stochastic driving behavior as well as their charging needs. Two types of participation will be modeled and compared: 1) EV direct provision of the ramp product; and 2) EV cooperation with conventional generators.

The rest of this paper is organized as follows. Section II describes the estimation of EV aggregated power capacity with their stochastic mobility considered. Section III proposes the model to involve EVs into the flexible ramp market. Section IV discusses EV potentials in improving the ramp rate of the conventional generator through cooperation; several indices are proposed in Section V to evaluate the system's flexibility; the numerical experiment is conducted in Section VI. Section VII gives the conclusion. The relationship among different sections is shown in Fig. 1.

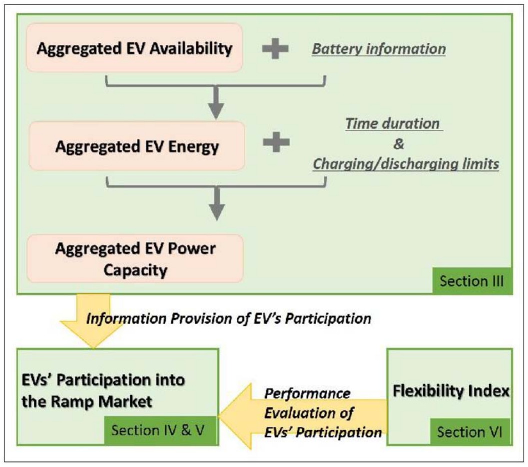


Fig. 1. Relationship among different sections.

II. ESTIMATION OF EV AGGREGATED POWER CAPACITY

In order to model EVs in the ramp market, it is instructive and critical for system operators to assess EV aggregated power capacity based on the stochastic driving behavior, which differentiates them from the conventional battery storage. Different from [20]–[26], an analytical method to estimate EV aggregated power capacity which takes into account different factors such as traffic information, accessibility to charging infrastructure, human's charging preferences, etc., is proposed.

A. *Estimation of EV Availability*

Those EVs that are parked (home, parking lot, side of the road, charging station, etc.) might be available to provide service to the power grid. Although there are some unsolved practical issues with EV V2G mode, we consider both G2V and V2G modes feasible like many other researchers in this field [15]–[17], [19], [20], [23]. In order to evaluate EV availability, we first estimate the number of EVs traveling on the road based on a homogeneous Markov model.

The flow of vehicles coming into the highway traffic is assumed to be a Poisson process [27]. If we assume that the whole traffic system is composed of a lot of entrances like highway, the equivalent vehicle flow into the traffic system can still be a Poisson process.

According to [28], when the traffic system can hold a huge number of vehicles, namely $m \to \infty$, the probability that there are k vehicles traveling on the roads is

$$P_{rb}(k) = \frac{\rho^k}{k!}e^{-\rho} \quad \rho = \frac{\lambda}{\mu} \quad k = 1, 2, \ldots, m. \tag{1}$$

If we assume that the total number of EVs in a large area is relatively stable, which is around N, the probability that there

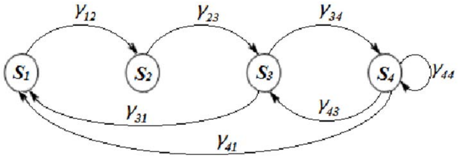


Fig. 2. Markov chain describing the state of individual EV.

are j EVs parked can be expressed in

$$P_{rb}^{\text{in}}(j) = \frac{\rho^{(N-j)}}{(N-j)!}e^{-\rho} \quad j = 1, 2, \ldots, m. \tag{2}$$

The parameters can be calibrated by the traffic condition data. As well known, traffic conditions vary over time; however, we assume that traffic conditions do not vary too much in one unit of time (e.g., 1 h). Based on hourly arrival and departure rates, we can estimate EV availability in different hours during one day [29].

B. Estimation of EV Energy for Charging/Discharging

EV aggregated energy capacity depends not only on their availability but also on how much energy each EV possesses. Markov model is adopted to help estimate the energy in one EV. Four states can be assigned to every EV: 1) S_1—traveling on the road; 2) S_2—parked but not plugged to the grid; 3) S_3—parked and plugged into the grid; and 4) S_4—parked and fully charged.

The Markov chain illustrating the transition among different states is shown in Fig. 2, where γ_{12} comes from the traffic data; γ_{23} is related to EV accessibility to charging infrastructures and drivers' willingness to plug their EVs to the grid; γ_{34} is related to the time needed for the vehicle to get fully charged; γ_{43} is determined by the frequency that EVs participate in the electricity market; and γ_{31} and γ_{41} are related to drivers' preferences, i.e., whether they choose to leave in the middle of the charging or after vehicles are fully charged. The information can be obtained from the survey conducted among EV drivers. Therefore, the state matrix can be expressed in (3) and the probability of EVs staying in state i can be calculated and denoted as P_{si} accordingly

$$\mathbf{B} = \begin{bmatrix} -\gamma_{12} & \gamma_{12} & 0 & 0 \\ 0 & -\gamma_{23} & \gamma_{23} & 0 \\ \gamma_{31} & 0 & -\gamma_{34} - \gamma_{31} & \gamma_{34} \\ \gamma_{41} & 0 & \gamma_{43} & -\gamma_{41} - \gamma_{43} \end{bmatrix}. \tag{3}$$

After obtaining the probability, we can estimate EV energy capacity by assuming that the energy of each vehicle follows a normal distribution. Assume that $E_{s23+} \sim N(\omega_{s23+}, \sigma_{s23+}^2)$ and $E_{s4+} \sim N(\omega_{s4+}, \sigma_{s4+}^2)$. Note that the mean value ω_{s23+} probably changes with the time, while ω_{s4+} can be assumed constant, and σ_{s4+}^2 is relatively small since the EV is fully charged at this state. Monitoring data on EV battery energy gathered from charging infrastructures can be utilized to statistically calibrate such parameters.

According to the properties of normal distribution, the energy that an EV holds when it is either in states S_3 or S_4 is still in normal distribution, $E_{s34+} \sim N(\omega_{s34+}, \sigma_{s34+}^2)$, where $\omega_{s34+}, \sigma_{s34+}^2$ can be calculated through

$$\omega_{s34+} = \frac{P_{S3}}{P_{S2} + P_{S3} + P_{S4}} \times \omega_{s23+} + \frac{P_{S4}}{P_{S2} + P_{S3} + P_{S4}} \times \omega_{s4+} \tag{4}$$

$$\sigma_{s34+}^2 = \left(\frac{P_{S3}}{P_{S2} + P_{S3} + P_{S4}}\right)^2 \times \sigma_{s23+}^2 + \left(\frac{P_{S4}}{P_{S2} + P_{S3} + P_{S4}}\right)^2 \times \sigma_{s4+}^2. \tag{5}$$

Combined with the availability obtained in (2), the cumulative distribution of EV available discharging energy at one moment can be expressed through

$$F_{Z+}(z) = \int_{-\infty}^{z} \sum_{j=1}^{m} \frac{\rho^{(N-j)}}{(N-j)!}e^{-\rho} \frac{1}{j\sqrt{2\pi}\sigma_{s34+}} e^{-\frac{\left(\frac{u}{j} - \omega_{s34+}\right)^2}{2\sigma_{s34+}^2}} du. \tag{6}$$

Then the probability density function of EV aggregated discharging energy is presented in (7). Following the same way, the cumulative distribution as well as the probability density of EV charging energy capacity can be obtained and represented as $F_{Z-}(z)$ and $f_{Z-}(z)$, respectively

$$f_{Z+}(z) = \sum_{j=1}^{m} \frac{\rho^{(N-j)}}{(N-j)!}e^{-\rho} \frac{1}{j\sqrt{2\pi}\sigma_{s34+}} e^{-\frac{\left(\frac{u}{j} - \omega_{s34+}\right)^2}{2\sigma_{s34+}^2}}. \tag{7}$$

From system operators' viewpoint, we can regard $F_{Z+}^{-1}(0.05)$ and $F_{Z-}^{-1}(0.05)$ as the exact amount of energy that EVs can discharge or charge, which indicates that the probability that EVs can provide or extract energy no less than that amount will be 95%. However, the battery depletion limit as well as EV energy needs for future travel should be taken into account when determining the discharging energy capacity. EV aggregated energy capacity for charging/discharging can be calculated in (8) and (9), where energy depletion limit is set to be 20%

$$\text{Energy}^{+} = F_{Z}^{-1}(0.05) - 0.2 \times C_{\text{EVtotal}} \times (N - \rho)/N - q \times \rho \tag{8}$$

$$\text{Energy}^{-} = F_{Z-}^{-1}(0.05). \tag{9}$$

C. Estimation of EV Charging/Discharging Power

Power is determined by two aspects: 1) energy and 2) time duration. Meanwhile, the available charging/discharging power is limited by EV maximum charging/discharging rates, too. EVs, if participating in the electricity market, should be able to provide stable power within some period (e.g., 1 h), to ensure sustained energy balancing. If we assume the time duration is h, the possible discharging power from EVs can be obtained through

$$\text{Power}^{+} = \text{Energy}^{+}/h. \tag{10}$$

Assume that the maximum discharging rate for one EV is $r^{+}_{\max}$, the limitation on EV power capacity caused by the discharging rate can be calculated through

$$\text{Limit}^{+} = r^{+}_{\max} \times n_p \times P_{S3}/(P_{S2} + P_{S3} + P_{S4}) \tag{11}$$

where n_p is determined from (12), which implies that there is above 95% probability that there are over n_p EVs parked

$$\min\left|P^{\text{in}}_{rb}(n_p) - 0.05\right| \text{ and } P^{\text{in}}_{rb}(n_p) \le 0.05. \tag{12}$$

Hence, EV aggregated discharging power capacity can be calculated by

$$p^{\max}_{\text{EV}+} = \min(\text{Power}^{+}, \text{Limit}^{+}). \tag{13}$$

EV aggregated charging power capacity $p^{\max}_{\text{EV}-}$ can be obtained through the similar process from (10)–(13).

III. EV'S PARTICIPATION IN THE RAMP MARKET

A. Background Information on the Ramp Product

The concept of the ramp product is proposed by California ISO and Midwest ISO to deal with the energy imbalance in RTD caused by the increasing penetration of renewables. The basic idea is to reserve the system's ramp capacity to handle the variable loads in the future. In order to integrate the ramp product in the wholesale market, the system's ramp need is evaluated and merged into the existing RTD model, as denoted by (23) and (24). The evaluation of the ramping need is based on the variation and uncertainty of the net load, and a certain confidence level shall be chosen to achieve the cost effectiveness.

For the sake of ensuring the ramp products being dispatched in RTD, a resource is required to have an energy bidding while participating in the ramp market. Separate bids on the ramp product, both upward and downward, are accepted. The ramp products are priced at the marginal values of the requirements. The capacity will receive flexible ramping payment once awarded and also the energy payment if dispatched.

B. Model of EV Participation in the Ramp Market

The look-ahead technique on a rolling horizon basis is adopted here so that.

1) The uncertainty and variation of the net load can be better dealt with.
2) EV charging needs can be better satisfied.

The correlation between driving habits of EV owners and the ramp scheme is based on four variables in (14)–(32): 1) $p_{\text{EVG}+}$; 2) $p_{\text{EVG}-}$; 3) FRU_{EV}; and 4) FRD_{EV}. Their upper limits are the aggregated power capacity assessed in Section II. The variable $p_{\text{EVG}+}$ is to ensure the timely release of EV ramp capacity when needed. The look-ahead dispatch model with EV participating in the ramp market is presented as follows:

$$\text{Min} \sum_{t=t_0}^{t_n} \left\{ \begin{array}{l} \sum_{i \in G}\left[C_{Gi}p^{t}_{Gi} + C_{\text{FRU}i}\text{FRU}^{t}_{i} + C_{\text{FRD}i}\text{FRD}^{t}_{i}\right] \\ +C_{\text{EVG}}p^{t}_{\text{EVG}+} + C_{\text{EVFRU}}\text{FRU}^{t}_{\text{EV}} + C_{\text{EVFRD}}\text{FRD}^{t}_{\text{EV}} \end{array} \right\} \tag{14}$$

$$\sum_{i \in G} p^{t}_{Gi} + p^{t}_{\text{EVG}+} = P^{t}_{L} + p^{t}_{\text{EVG}-} \quad t = t_0, t_1, \ldots, t_n \tag{15}$$

$$p^{\min}_{Gi} \le p^{t}_{Gi} \le p^{\max}_{Gi} \quad i \in G, t = t_0, t_1, \ldots, t_n \tag{16}$$

$$0 \le \text{FRU}^{t}_{i} \le R_i \times \Delta t \quad i \in G, t = t_0, t_1, \ldots, t_n \tag{17}$$

$$0 \le \text{FRD}^{t}_{i} \le R_i \times \Delta t \quad i \in G, t = t_0, t_1, \ldots, t_n \tag{18}$$

$$p^{t}_{Gi} + \text{FRU}^{t}_{i} \le p^{\max}_{Gi} \quad i \in G, t = t_0, t_1, \ldots, t_n \tag{19}$$

$$p^{t}_{Gi} - \text{FRD}^{t}_{i} \ge p^{\min}_{Gi} \quad i \in G, t = t_0, t_1, \ldots, t_n \tag{20}$$

$$p^{t}_{Gi} - p^{t-1}_{Gi} \le R_i \times \Delta t \quad i \in G, t = t_0, t_1, \ldots, t_n \tag{21}$$

$$p^{t-1}_{Gi} - p^{t}_{Gi} \le R_i \times \Delta t \quad i \in G, t = t_0, t_1, \ldots, t_n \tag{22}$$

$$\sum_{i \in G} \text{FRU}^{t}_{i} + \text{FRU}^{t}_{\text{EV}} \ge D^{t}_{\text{FRU}} \quad t = t_0, t_1, \ldots, t_n \tag{23}$$

$$\sum_{i \in G} \text{FRD}^{t}_{i} + \text{FRD}^{t}_{\text{EV}} \ge D^{t}_{\text{FRD}} \quad t = t_0, t_1, \ldots, t_n \tag{24}$$

$$0 \le p^{t}_{\text{EVG}+} \le p^{\max,t}_{\text{EV}+} \quad t = t_0, t_1, \ldots, t_n \tag{25}$$

$$0 \le p^{t}_{\text{EVG}-} \le p^{\max,t}_{\text{EV}-} \quad t = t_0, t_1, \ldots, t_n \tag{26}$$

$$E^{t-1}_{\text{EV}} - E^{t}_{\text{EV}} = \left(\frac{1}{\eta^{+}}p^{t}_{\text{EVG}+} - \eta^{-}p^{t}_{\text{EVG}-}\right) \times \Delta t \quad t = t_0, t_1, \ldots, t_n \tag{27}$$

$$E^{t}_{\text{EV}}\big|_{t=t_k} \ge C_{\text{req}} \tag{28}$$

$$p^{t}_{\text{EVG}+} - p^{t}_{\text{EVG}-} + \text{FRU}^{t}_{\text{EV}} \le p^{\max,t}_{\text{EV}+} \quad t = t_0, t_1, \ldots, t_n \tag{29}$$

$$p^{t}_{\text{EVG}+} - p^{t}_{\text{EVG}-} - \text{FRD}^{t}_{\text{EV}} \ge -p^{\max,t}_{\text{EV}-} \quad t = t_0, t_1, \ldots, t_n \tag{30}$$

$$0 \le \text{FRU}^{t}_{\text{EV}} \le p^{\max,t}_{\text{EV}+} \quad t = t_0, t_1, \ldots, t_n \tag{31}$$

$$0 \le \text{FRD}^{t}_{\text{EV}} \le p^{\max,t}_{\text{EV}-} \quad t = t_0, t_1, \ldots, t_n. \tag{32}$$

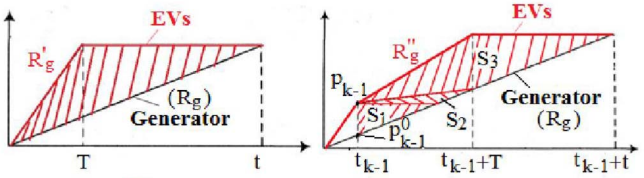
The objective function (14) is to minimize the total cost. Equation (15) is the power balance equation at different time intervals. Equations (16)–(22) enforce the constraints on generators' outputs caused by their generation and ramp limits; system's ramp requirements, both ramp up and down, are enforced through (23) and (24).

Equations (25) and (26) express the generation limit for EVs, where $p^{\max,t}_{\text{EV}+}$ and $p^{\max,t}_{\text{EV}-}$ are EV aggregated discharging and charging power capacity obtained through the method addressed in Section II.

Equation (27) is EV energy dynamic equation [30], which tracks EV energy in every interval, where η^{+} and η^{-} should be valued between 0 and 1. Equation (28) is the energy requirement equation of EVs which ensures that EV energy, at time interval t_k, must be greater than or equal to the requirement, marked by C_{req}.

Equations (29)–(32) are the combined constraints on EV energy provision and their capability to provide the ramping service.

It is inevitable that inconvenience may occur to EV drivers due to EV participation in the electricity market. Therefore, incentive mechanisms become indispensable to encourage EV involvement. Several incentives have been introduced in [18], [31], and [32], such as price discount for EV charging, benefit rewarded based on the service provided, and so on. Those incentive mechanisms can also apply in the case of EV providing the ramp product.



(a) (b)

Fig. 3. Illustration of EV cooperation with conventional generators. (a) Scenario 1. (b) Scenario 2.

IV. EV Cooperation With Conventional Generator

A. *Calculation of the Equivalent Ramping Rate*

Although it is hard for EVs to provide sustainable power like conventional generators, they can ramp up or down very quickly if needed. For those generators with relatively low ramp rates, the cooperation with EVs can enable them to improve their ramp capabilities.

The basis of EV improving generator's ramp rate is to utilize EV ramp capacity until the generator can catch up with the new generation point, as illustrated in Fig. 3. The red shade denotes the energy provided by EVs and the black line denotes the operation of the conventional generators. T is the time base for the ramp product.

Three factors exert restriction on the equivalent ramp rate: 1) the available energy that EVs can charge or discharge; 2) the maximum power EVs can provide; and 3) the generation limit of the conventional generator.

If we take the process of ramping up for example, the first scenario shown in Fig. 3(a) lies in the situation when EVs do not discharge, or EVs are charging at the very beginning. The constraint caused by EV energy capacity can be expressed in (33), which means the area of the red triangle is less than the aggregated EV available energy, and the corresponding maximum ramping rate is presented

$$(t - T) \times R_g \times t/2 \leq \text{Energy}^+ \tag{33}$$

$$R_{g1} = \left(T + \sqrt{T^2 + 8 \times \text{Energy}^+/R_g}\right) \times R_g/(2T). \tag{34}$$

Meanwhile, the limitation results from EV power output and the maximum ramp rate accordingly are expressed in (35) and (36). This suggests that the power provided by EVs should not exceed their maximum power output limit at any time

$$R_{g2} \times T - R_g \times T \leq p^{\max}_{\text{EV}+} \tag{35}$$

$$R_{g2} = p^{\max}_{\text{EV}+}/T + R_g. \tag{36}$$

Moreover, the constraint due to the maximum generation limit is calculated in (37). The ultimate equivalent output should not exceed the maximum output of the generator due to the limitation on EV energy capacity

$$R_{g3} = (p^{\max}_G - p_G)/T. \tag{37}$$

Therefore, the new maximum ramp rate should be the minimum of these three results, as expressed

$$R'_g = \min(R_{g1}, R_{g2}, R_{g3}). \tag{38}$$

The second scenario, as shown in Fig. 3(b), appears when EVs are discharging at the beginning of the new interval and they are selected to cooperate with the generator again. This suggests the aggregated output of both EVs and the generator at the beginning is actually higher than that of the generator itself. In Fig. 3(b), P^0_{k-1} is the output of the generator, and P_{k-1} is the equivalent output at the interval t_{k-1}.

Following the same procedures above, we can calculate the new ramp rate as follows:

$$R''_g = \min\left(R'_{g1}, R'_{g2}, R'_{g3}\right) \tag{39}$$

$$R'_{g1} = \begin{cases} \left(P^0_{k-1} + R_g \times T - P_{k-1}\right)/T, & \text{if Energy}^+ < S_1 + S_2 \\ \left(P^0_{k-1} + R_g \times t_{\max} - P_{k-1}\right)/T, & \text{otherwise} \end{cases} \tag{40}$$

$$t_{\max} = \left(T + \sqrt{T^2 - \left[4 \times \left(P_{k-1} - P^0_{k-1}\right) \times T - 8 \times \text{Energy}^+\right]/R_g}\right)/2 \tag{41}$$

$$R'_{g2} = \left(p^{\max}_{\text{EV}+} + R_g \times T + P^0_{k-1} - P_{k-1}\right)/T \tag{42}$$

$$R'_{g3} = \left(p^{\max}_G - P_{k-1}\right)/T. \tag{43}$$

Similarly, the way to obtain the aggregated ramp rate to ramp down also depends on two scenarios and can be obtained through (33)–(43).

B. *Cooperation Strategy and Its Related Modification to the Look-Ahead Model*

Due to the fact that EVs may not be able to provide stable power for a long time, the conventional generator will lose the capability to ramp up even while cooperating with EVs once reaching its upper/down limits and this may restrict EV participation in the ramp market through the mere cooperation. Therefore, the strategy for EVs in this paper is first to cooperate with the conventional generator as much as possible, and the spare capacity of EVs will be allowed to provide the ramp service on their own.

Consequently, the model proposed in Section III needs to be modified accordingly. We assume that EVs are cooperating with the k^{th} generator. The ramp rate of the k^{th} generator should be calculated and modified based on the method proposed in Section IV-A. Two parameters, $p^{g,t}_{\text{EVG}+}$ and $p^{g,t}_{\text{EVG}-}$, are added to denote the portion of power that EVs adopt to cooperate with the generator.

Among (19) and (20), all those related to generator k need to be modified as

$$p^t_{Gk} + \text{FRU}^t_k + p^{g,t}_{\text{EVG}+} - p^{g,t}_{\text{EVG}-} \leq p^{\max}_{Gk} \tag{44}$$

$$-p^t_{Gk} + \text{FRU}^t_k - p^{g,t}_{\text{EVG}+} + p^{g,t}_{\text{EVG}-} \leq -p^{\min}_{Gk}. \tag{45}$$

The generation constraints related to EVs, as presented in (29) and (30), should be modified into

$$p^t_{\text{EVG}+} - p^t_{\text{EVG}-} + \text{FRU}^t_{\text{EV}} + p^{g,t}_{\text{EVG}+} - p^{g,t}_{\text{EVG}-} \leq p^{\max}_{\text{EV}+} \tag{46}$$

$$-p^t_{\text{EVG}+} + p^t_{\text{EVG}-} + \text{FRU}^t_{\text{EV}} - p^{g,t}_{\text{EVG}+} + p^{g,t}_{\text{EVG}-} \leq p^{\max}_{\text{EV}-}. \tag{47}$$

Meanwhile, the power balance equation, as expressed in (15) should be modified to

$$\sum_{i \in G} p^t_{Gi} + p^t_{\text{EVG}+} + p^{g,t}_{\text{EVG}+} = P^t_L + p^t_{\text{EVG}-} + p^{g,t}_{\text{EVG}-}. \tag{48}$$

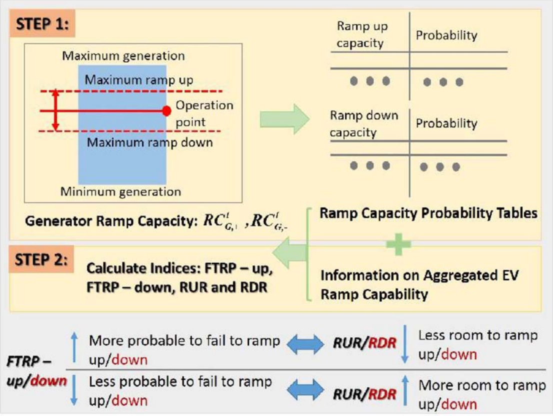


Fig. 4. Calculation steps and relationships between the flexibility indices.

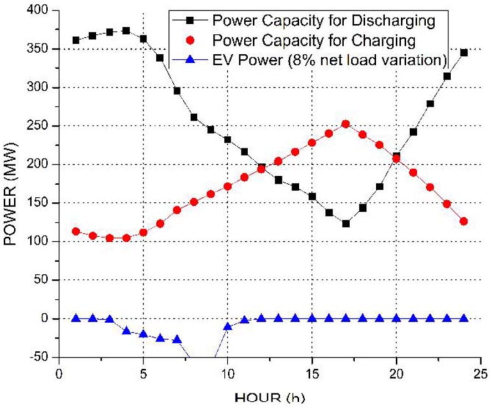


Fig. 5. EV aggregated power capacity and power during one day.

And the energy dynamic equation in (27) should be modified as (49), where $t = t_0, t_1, \ldots, t_n$ from (44)–(49)

$$E^{t-1}_{\text{EV}} - E^t_{\text{EV}} = \left(\frac{1}{\eta^+} p^t_{\text{EVG}+} - \eta^- p^t_{\text{EVG}-} + \frac{1}{\eta^+} p^{g,t}_{\text{EVG}+} - \eta^- p^{g,t}_{\text{EVG}-}\right) \times \Delta t. \quad (49)$$

Last but not least, the up and down limits of the two newly added variables need to be set properly.

V. EV IMPACT ON POWER SYSTEM FLEXIBILITY

Ever since the flexible ramping products were proposed, several studies have been conducted to evaluate power system flexibility [33]–[35]. It is pointed out that generators' ramp capacities, which enable the system's flexibility in dealing with uncertainty and variation, are not independent of each other.

We propose to use the probability that the system fails to meet the ramp requirement, fail to ramp probability (FTRP-up and FTRP-down), to assess the flexibility based on certain market clearing results, under which circumstances, the correlations among generators' ramp capacities can be greatly reduced.

There are two main steps to calculate the FTRP-up and FTRP-down indices.

Step 1: Calculate the ramp capacities for generators according to (50) and (51), where x_i indicates the on/off states of the ith generator

$$RC^t_{Gi,+} = x_i \times \min\left(R_i \times \Delta t, p^{\max}_{Gi} - p^t_{Gi}\right) \quad (50)$$

$$RC^t_{Gi,-} = x_i \times \min\left(R_i \times \Delta t, p^t_{Gi} - p^{\min}_{Gi}\right). \quad (51)$$

Then two tables consisting of the ramp capacities (ramp up/down capacities) and the corresponding probabilities can be formed similarly to the capacity outage probability table.

Step 2: Calculate the desired probability with EV participation based on the tables obtained in step 1. Assume that generators' total capacity for ramp up at time interval t is $RC^t_{G,+}$, the ramp up requirement at time interval t is D^t_{FRU}, and the probability that generators have x MW loss of ramp up capacity is denoted as $P_{rbU}(x)$. The FTRP-up is calculated as (52) and FTRP-down is calculated in the similar way.

Sometimes, the results of the index FTRP-up or FTRP-down are too close to distinguish. Therefore, two other indices are proposed: 1) ramp up room (RUR); and 2) ramp down room (RDR), which indicate how much the system will be able to ramp up or down under a certain probability P_{rb}. RUR can be calculated through the inverse function of FTRP-up as presented in (53). And RDR can be calculated in the similar way. Illustration of the steps and the relationship between different indices are shown in Fig. 4

$$\text{FTRP} - \text{up}\left(D^t_{\text{FRU}}\right) = \sum_{x=0}^{RC^t_{G,+}} P_{rbU}(x) F_{Zp+}\left(D^t_{\text{FRU}} - RC^t_{G,+} + x\right) \quad (52)$$

$$\text{RUR} = \text{FTRP} - \text{up}^{-1}(p_{rb}). \quad (53)$$

VI. NUMERICAL EXPERIMENT AND ANALYSIS

A. EV Aggregated Power Capacity

EVs are gaining more and more market share nowadays. Over 100 000 units were sold through August 2014 in California [36]. In this paper, we assume the system has 30 000 EVs, half of which are Nissan Leaf whose battery size is 24 kWh. The other half of EVs are Chevy Volt with a battery size of 16 kWh. Traffic condition data come from [37], according to which the daily vehicle trips is 3.02 times, and daily vehicle miles traveled is 28.97 miles. If the average speed is assumed to be 40 miles per hour, the average travel time for a vehicle is about 14 min [(28.97/3.02/40) * 60]. Therefore, μ is around four times per hour. Meanwhile, we assume that every EV will need around 0.35 kW to travel one mile, which means q is around 3.36 kW [0.35 * 28.97/3.02]. It is also assumed that EV accessibility to charging infrastructures is 0.9.

Based on the approach addressed in Section II, the available power that EVs can charge and discharge during one day is obtained and illustrated in Fig. 5, which can be the upper limits of the ramping service that EVs can provide.

TABLE I
NET LOAD FORECAST

Forecast (MW)	T1	T2	T3	T4
T1	2531	2503		
T2		2600	2700	
T3-Case 1			2850	2600
T3-Case 2			2900	2600

TABLE II
ENERGY PRICE UNDER FOUR SCENARIOS

Energy Price ($)	Scenario 1	Scenario 2	Scenario 3	Scenario 4
T1	27.5688	27.5688	27.5688	26.7796
T2	27.5688	27.7537	27.5688	27.5688
T3-Case 1	211.1405	58.6814	-	211.141
T3-Case 2	211.1405	-	-	211.141

B. Impact of EV Participation in the Ramp Market

A modified IEEE-RTS 96 test case system is selected to conduct the simulation on EV participation in the ramp product market. The detailed connections of different buses can be found in [38, Fig. 4]. The information on generators including their capacities, forced outage rate, connections, etc., can be obtained from [38, Tables VI–X]. The simulation duration is 24 h. The dispatch interval is 10 min. Load profile for 48 h is collected from the ERCOT system [39]. EV energy requirement requests the state of charge higher than 80% of the battery capacity at the beginning of the second day. The EVs are located at bus 114 (9000 EVs), 115 (18 000), and 116 (3000) and their cost of providing the ramp service is assumed to be \$5.44/MWh.

In this wholesale market, an EV aggregator, as described in [18], represents all the EVs in the ramp market. The market results under four scenarios are compared: 1) a market with EV provision of the ramp product; 2) a market with the ramp product, but EVs just act as loads; 3) a market without the ramp product and EVs act as loads; and 4) a market with EV provision of the ramp product and EVs cooperate with one conventional generator (U155 at Bus 115).

Table I shows the net load forecast. One-interval market clearing results are listed in Table II. The symbol "–" in Table II means that the system lacks the capacity to clear the market. When this happens, the system can just rely on other products in the electricity market such as frequency regulation with a higher cost. In MISO, the price associated with system power balance constraint violation is assumed to be the value of lost load, which is \$3500/MWh [11].

We can observe from Tables I and II that with the ramp products involved (scenarios 1, 2, and 4), the electricity market, which is originally infeasible (scenario 3), can now be cleared in case 1. Moreover, EV provision of the ramp product (scenarios 1 and 4) can further enable the market to be cleared in case 2, when the load variation is higher than that in case 1. The results show the following.

1) The ramp product can help system better handle the variation and uncertainty.
2) EV provision of the ramp product can further improve the system's flexibility, since more room is obtained to handle the variation and uncertainty.

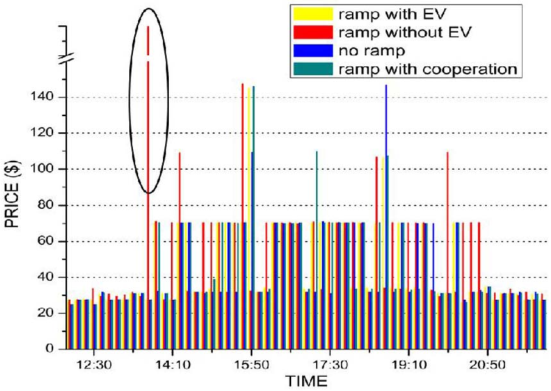


Fig. 6. Energy price under different scenarios (6% net load variation).

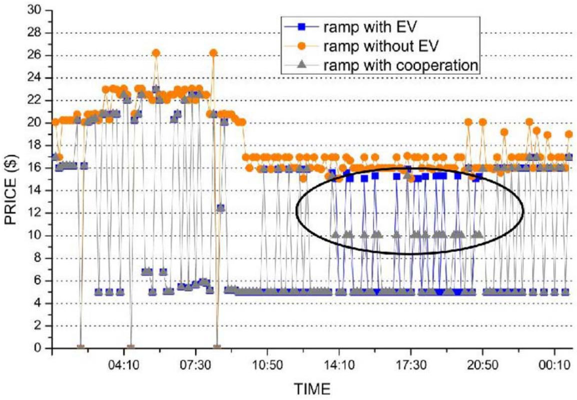


Fig. 7. Ramp-down price under 6% net load variation.

Although the energy prices are higher, EV participation can help prevent price spikes due to the insufficiency of capacity when the net load is highly variable.

Then the 24-h look-ahead simulation is conducted under different net load variations ranging from 1% to 8%. Fig. 6 illustrates the energy prices under four scenarios when net load variation is at 6%. It is observed that there is one moment when the energy price is extremely high for scenario 2, which is circled in black. This is because the ramp requirement increases accordingly with the growing net load uncertainty and variation. Such increase could lead to insufficiency in the ramp capacity, although the net load demand can still be satisfied. The involvement of EVs in the ramp product market can help mitigate price spikes because their fast ramping capability can enhance the system's flexibility.

EV another contribution is illustrated in Fig. 7. With EV participation, the price of the ramp products is lowered down in both scenarios 1 and 4. This is due to EV relatively lower cost of providing ramping services.

Table III compares the system costs in different net load variations, and it shows that the cost will increase when the ramp product is integrated. However, an improvement in cost

TABLE III
SYSTEM COST UNDER DIFFERENT SCENARIOS

Cost ($)		Scenarios			
		No.1	No.2	No.3	No.4
Net load Variation	1%	1110358	1135591	1111111	1110097
	2%	1119107	1160420	1113580	1119039
	3%	1126841	1185118	1113264	1126505
	4%	1136544	1213335	1113212	1135015
	5%	1146267	1244856	1110727	1145796
	6%	1165168	1281181	1115552	1163985
	7%	1187228	1323758	1117879	1183974
	8%	1206859	1357614	1114052	1203468

TABLE IV
EV CHARGING COST UNDER DIFFERENT SCENARIOS

Charging Cost ($)		Scenarios			
		No.1	No.2	No.3	No.4
Net load Variation	1%	1615	48801	48606	1596
	2%	1609	47965	47617	1605
	3%	1623	48902	48583	1624
	4%	1631	54548	47408	1632
	5%	1861	53517	48622	1863
	6%	2036	53562	48448	2016
	7%	1935	61609	45819	1935
	8%	2223	362023	49673	2532

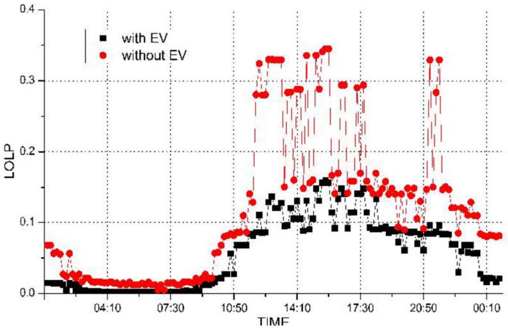


Fig. 8. Illustration of LOLP result (5% net load variation).

saving can be achieved by enabling EVs to provide the ramp product. Two main reasons contribute to this finding.

1) EVs have relatively low cost in providing the ramp service.
2) The intelligent charging scheme, which is embedded in the proposed model, can reduce EV charging cost compared with the dumb charging in scenarios 2 and 3.

The charging cost is shown in Table IV.

According to [28], we calculate the loss of load probability (LOLP) of the system with and without EV participation in the ramp market, and the results show that the involvement of EVs can improve the system's reliability. Fig. 8 shows the LOLP results when the net load variation is 5%.

Figs. 9 and 10 illustrate the system's flexibility results when net load variation is 8%. We can observe that the introduction of the ramp product can improve the system's flexibility. With the ramp product involved, the system has higher probability to meet the ramp requirement. In addition, it has more RUR. P_{rb} in (53) is set to 0.001 to obtain Fig. 10, which indicates that the system can deal with more uncertainty and variation within the probability of 99.9%. Another observation is that EV providing the ramp product can further improve the system's flexibility, since the results of FTRP-up and RUR get further improved after EVs are enabled to participate in the ramp market.

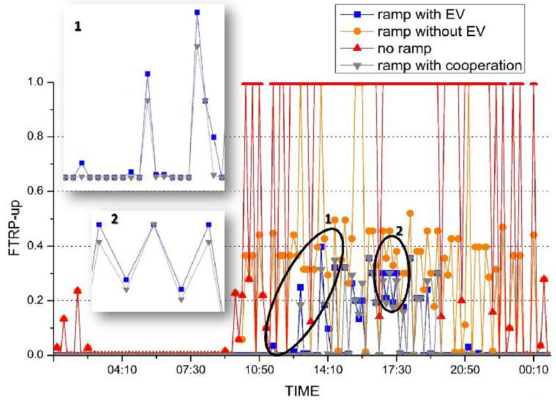


Fig. 9. Illustration of FTRP-up result (8% net load variation).

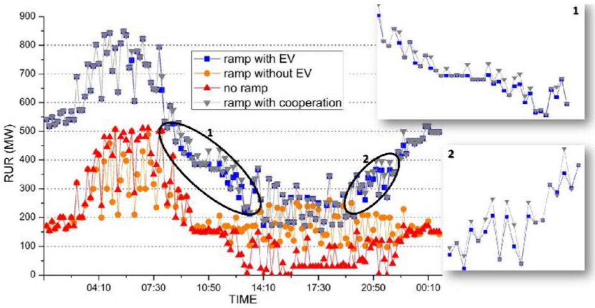


Fig. 10. Illustration of RUR result (8% net load variation).

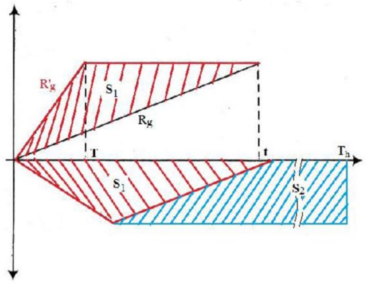


Fig. 11. Difference between EV cooperation with the conventional generator or not.

C. Impact of EV Cooperation With Conventional Generator

There are mainly two factors resulting in the differences between EVs cooperation with the conventional generator and their direct participation. First, EVs will have less capacity to provide the ramp product, if cooperating with the conventional generator first. This could lead to more reservation on ramp capacities for other generators in the system. Second, the cooperation with the conventional generator can help exploit EV ramping capability, and this is well exhibited in Fig. 11. The upper part of Fig. 11 is quite similar to Fig. 3(a), and in order to obtain the equivalent ramp rate $R_g^{'}$, the energy equal

TABLE V
TOTAL BENEFIT FOR EVS AND THE GENERATOR (U155 AT BUS 115)

Benefit ($)	Net load Uncertainty and Variation			
	1%	2%	3%	4%
No cooperation	15263	15642	22717	25106
With cooperation	15311	15646	22748	25992
Benefit ($)	Net load Uncertainty and Variation			
	1%	2%	3%	4%
No cooperation	47340	60839	74016	100474
With cooperation	47465	61086	77840	111070

to S_1 will be needed from EVs. However, if the cooperation is not enabled, energy that equals to $S_1 + S_2$ will be needed from EVs to achieve the same equivalent ramp rate. Less energy from EVs is required to achieve the desired ramp rate with the cooperation. This might not be the case if the situation illustrated in Fig. 3(b) happens. However, the ramp capacity will be rarely called in reality owing to the fact that a high uncertainty event will not happen that often. Therefore, the situation illustrated in Fig. 3(b) rarely happens.

Due to the further utilization of EV ramp capability, the cooperation shows some further advantages over EV direct participation in the ramp market. As shown in the black circle in Fig. 7, the prices of the ramp down service tend to be lower when the cooperation is enabled. Besides, the results show the further improvement in the system's flexibility, circled in black in Figs. 9 and 10, when EVs cooperate with the conventional generator. The improvement will be more obvious when the net load uncertainty and variation are increased.

Meanwhile, the cooperation shows a potential to help make more profit for both EVs and the designated generator, as illustrated in Table V. This analysis assumes that the profit rate is 3% for both EVs and the generator. Such increase in profit can be an incentive for the widespread use and development of EV charging/discharging stations.

In addition, the following discusses the impact of EV participation in the ramp market from EV side. During the simulation, we found that although EVs take the majority in the ramp product, they seldom get called to provide energy back to the system, as illustrated in Fig. 5. Therefore, EVs, in most cases, serve as a backup for dealing with huge uncertainty and variation. This attribute is beneficial for EV operation, since.

1) They do not have to discharge quite often.
2) Their capability of fast ramping up/down can be rewarded accordingly.
3) Their charging can be optimized and charging cost can be reduced.

VII. CONCLUSION

The main contributions of this paper are as follows.

1) Analytical estimate of EV aggregated charging/discharging power capacity taking into account EV stochastic mobility and drivers' behavior.
2) Exploration of EV potential in improving the ramp rate of conventional generators through cooperation.
3) Proposed models to involve EVs into the flexible ramp market, for both EV direct participation and cooperation with generators, with EV charging need and charging/discharging efficiency considered.
4) Proposed new indices to evaluate the power system's flexibility under certain market clearing results.
5) Numerical experiment conducted to understand the impact of EV participation in the ramp market on the system's reliability and flexibility as well as on EVs themselves.

The limitation of the proposed market model is the lack of integration of other ancillary services such as reserve, regulation, etc. The possible extensions would be.

1) Improve the market model by integrating other ancillary services.
2) Estimate the aggregated EV availability by nonhomogenous Markov model.
3) Economically evaluate the cost of EVs providing the ramp product.
4) Study the incentive scheme for EV participation in the ramp market.

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