Reliability assessment of frequency regulation service provided by *V2G*

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***Abstract*—A framework to quantify reliability of frequency regulation service offered by *V2G* using Markov reliability models. The framework incorporates key features of *V2G* aggregation and the requirements of the *ISO* on regulation resources.The approach is particularly useful to analytically determine the number of *EV*s required to meet the *ISO* performance requirements on regulation resources. The paper also computes the sensitivity of the reliability of the service to the duration for which *EV*s are available to provide the service,also termed as "availability" of *EV*s. Through the sensitivity analysis, the effect of parameter uncertainty on the reliability can be estimated. The proposed approach is illustrated using a sample aggregation described in the paper that offers regulation capacity in the PJM ancillary services market.**

***Index Terms*—Reliability, *V2G*, Electric Vehicles, *EV*s, *ISO*, frequency regulation, sensitivity analysis.**

I. Introduction

Growth in electric vehicle (*EV*) sales has presented an attractive opportunity for the development of Vehicle-to-Grid (*V2G*) systems. The concept of *V2G* framework is to employ *EV*s to provide ancillary and possibly energy services to the electricity grid during the time *EV*s are not in use, for which *EV* owners are compensated. The fast response time of *EV* batteries (of the order of ms) makes *V2G* particularly suitable for provision of frequency regulation ancillary service. Frequency regulation is also lucrative in terms of revenue generation. The market-clearing price for regulation service lies in the range of $15 - 40$ \$/MW-h, one of the highest among ancillary services. However, provision of such services requires the aggregation of a sufficiently large number of *EV*s, since the battery storage capability/capacity of an individual *EV* is not palpable to the grid. Such aggregations can be created by a new player in the V2G framework called the aggregator [1]. Pilot *V2G* projects are currently under implementation in various parts of the US, including Los Angeles Air Force Base (CAISO, SCE, LBNL and DOD) [2] and Grid on Wheels (PJM, University of Delaware, Autoport Inc., Milbank, NRG, *EV*Grid, and eV2g) [3]. These projects aim to demonstrate the feasibility of the idea and benefits of the *V2G* framework when used for provision of frequency regulation.

We now digress from V2G to talk about the *ISO* ancillary service (AS) markets. Resources offer bids in the *ISO* market to provide service(s) for specified cost(s). The *ISO* then runs the market to determine hourly market-clearing prices and unit commitments, which produce the least cost of the services procured while meeting reliability needs. For a service to be certified as a "resource" that can participate in the AS markets, it must meet NERC standards and pass the tests required by the *ISO*. Once certified as a "qualified resource", the service becomes a participant in the *ISO* markets. Furthermore, to maintain its "qualified" status, the resource must also pass the regular announced and unannounced performance audits carried out by the *ISO*. For resources that provide frequency regulation, the audit entails the calculation a performance score that reflects the benefits that the regulation resource provides to system controls. This performance score is calculated by focusing on the resource's response to *ISO* control signals and is based on two metrics: mileage[1] and regulation capability (in MW) offered in *ISO* market. A resource is disqualified if the performance score drops below a performance threshold specified by the *ISO*. Resources that do not meet the performance requirement are disqualified and have to re-qualify to participate in the *ISO* market. Thus, performance score is a good indicator of the reliability of a regulation resource.

Like any regulation resource, frequency regulation from V2G framework has to be certified as a resource and pass the performance audit tests to be able to participate in the *ISO* markets. However, issues in practical implementation persist. One such issue is related to *EV* mobility. We describe two scenarios that arise:

1) The aggregator prohibits *EV* owners from using their *EV*s for a given number of hours specified in the V2G contract. As the total capacity of the aggregation becomes fixed in those hours,the aggregator can ensure the provision of highly reliable *V2G* service to the *ISO* which meets the reliability requirements of the *ISO*. However, mobility constraints may make *EV* owners reluctant to participate in V2G framework. Low participation leads to a revenue reduction for the aggregator
2) *EV*s are allowed to leave the aggregation. The capacity of the aggregation at any point of time is no longer fixed as *EV*s enter and leave the aggregation stochastically. Therefore, the actual regulation capability available at

[1] Mileage is defined as the regulation provided in an hour and is calculated as the sum of the absolute value of positive and negative movements requested by the *ISO* while providing regulation (net of any generator working against the ACE

any point of time may be different from the capability that has been offered by the aggregator in the *ISO* market in such scenarios. While this may not be an issue in a few fortunate cases where the *ISO* does not request the full regulation capability offered by the resource, in most of the other scenarios it may severely affect the capability component of the performance score. As such, there is no guarantee that the *V2G* regulation service can pass the qualification tests and performance audits at all times. This can lead to resource disqualification or penalization by the *ISO* for poor performance.

We observe that the scenarios described above present a trade-off for the aggregator between provision of reliable regulation service to the *ISO* and attracting maximum participation in the aggregation by *EV* owners.

In this paper, we do a comprehensive analysis of the reliability of the frequency regulation service offered by *V2G* framework to address the described problems. Our approach captures the dynamic nature of *EV* aggregation as well as the *ISO* requirements on regulation resources. Literature that discusses the above issues is limited. Our work is related [4], in which the authors demonstrate impact of the battery state of charge (*soc*) constraints on reliability and propose the use of Markov Models to assess the reliability of the *V2G* regulation service. To perform the analysis, we use the definition of reliability of the *V2G* regulation resource as *the probability that aggregator can provide the regulation by the* ISO *when the* V2G *service is awarded a regulation capacity that is equal to the sum of the battery capacities of all the EVs enrolled in the aggregation by the* ISO.

A second aspect of our approach is to reduce constraints on *EV* mobility. We permit some of the *EV*s to leave the aggregation and study its effect on the reliability of the service. We assume that there are no ramping limitations that may affect the mileage component of performance score. This assumption is reasonable due to the very fast response time of batteries (of the order of ms). Therefore, only the impact of the loss of regulation capability due to change in aggregation size on performance scores is investigated. The analysis also incorporates the control signal data from the *ISO* in the model to ensure that the *V2G* capacity is represented under all possible regulation states requested by the *ISO*. Through such a study, the tradeoff between *EV* mobility constraints and reliability can be quantified so that the aggregator can relax restrictions on *EV* mobility to the extent that they do not unduly affect the reliability of the service. As such, the aggregator will be able to analytically determine if the V2G regulation service can pass the performance audits carried out by the *ISO* and therefore, can maintain its status as a "qualified resource".

Markov models have the capability to describe complex systems through simplistic mathematical approaches. They can capture the failure of a component and its subsequent repair. They also allow us to describe de-rated states of a component where the component may not be fully functional, but partially delivers its functionality. These features make Markov models well suited to our purpose.

While the percentage of time *EV*s are idle to provide *V2G* service (also termed as "availability" of *EV*s) has been experimentally evaluated in [5] and [6] the modelings of the rates at which *EV*s enter and leave the aggregation have not been discussed. Therefore, we also analyze the impact of parameter uncertainty on reliability and performance metrics. This is an important aspect of system reliability/performance analysis, because it is difficult to ascertain the rates at which *EV*s leave or join the aggregation.

The rest of the paper is organized as follows: Section II formulates Markov models for reliability and performance evaluation, and proposes a method to compute the stationary distribution of Markov chain, and its sensitivity to model parameters variations. Case study in Section III demonstrates how the proposed framework can be employed to determine the reliability of a given *V2G* aggregation. Concluding remarks are presented in Section IV and scope of future work is given in Section V

II. Model formulation and reliability assessment

A. Model of the aggregation

The aggregator intends to attract maximum participation to his aggregation; therefore, we assume that the aggregator wishes to impose minimum constraints on mobility of the *EV*s. In this section, we model an aggregation that permits *EV*s to leave and join the aggregation and also ensures that the *ISO* minimum capacity requirements on regulation resources are met.

Consider a *V2G* fleet of m cars. For the sake of simplicity, we assume that all the cars are identical and therefore have identical battery characteristics. The battery capacity of an individual car in the aggregation is denoted by c kW. Additionally, each *EV* leaves (joins) the aggregation independently. The rate at which an *EV* leaves (joins) the aggregation is denoted by $\lambda(\mu)$. A second assumption is that at any point in time, only n *EV*s are allowed to leave the aggregation. We impose this constraint on the aggregation as any regulation resource must have a minimum capacity at all times to be able to offer its capacity in the AS market. Thus $m - n$ cars are present in the fleet at all times. We note that when an *EV* leaves the aggregation, it causes a loss of regulation capacity in both up and down directions. Lastly, we use the term "availability" of an *EV* to express the probability that an *EV* is present in the fleet to provide regulation service and denote the "availability" by p. p has been experimentally calculated in [5] and [6]. p can also be computed from the equation 1

$$p = \frac{\mu}{\lambda + \mu} \tag{1}$$

With these constraints in mind, the aggregation can now be treated as a single component that can function in derated states. The derated states are described by a finite set $S = \{0, 1, 2, ..., n\}$, where any $i \in S$ denotes capacity state c_i that results when i *EV*s leave the aggregation. Thus, 0 denotes the state with regulation capacity $c \cdot k$ kW, in which all the *EV*s are present in the aggregation. State 0 is analogous to the failure free configuration of a component. Transition from a state i to state $i+1$ occurs when *EV*s leave/join the aggregation. Thus, transition intensity from a state i to state $i+1$ is $(m-i)\lambda$ because any one of the $(m-i)$ *EV*s can leave the aggregation. Similarly, transition intensity from a state $(i+1)$ to state i is $(i+1)\mu$ as any of the $i+1$ *EV*s can join the aggregation. In our work, we use Δt to be the smallest indecomposable unit of time and assume that in Δt only transitions that involve a single *EV* leaving (joining) the aggregation are permitted. The model for the aggregation is drawn in Figure 1.

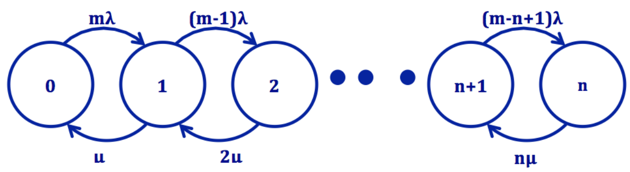

Fig. 1. Markov model representation of the *EV* aggregation

To compute the long-run probabilities that the aggregation is in state i in the set S we make use of Markov models. Let $X = \{X(t), t \geq 0\}$ denote a Markov chain taking values in the finite set $S = \{0, 1, 2, ..., n\}$. We use $\pi_i(t), t \geq 0$, to denote the probability that the system is in state i, and define the corresponding probability vector as $\pi(t) = [\pi_0(t), \pi_1(t), ..., \pi_n(t)]$. The evolution of $\pi(t)$ is defined by the Chapman-Kolmogorov equations

$$\dot{\pi}(t) = \pi(t)\Lambda \quad (2)$$

with $\pi_0(0) = 1, \pi_j(0) = 0, j = 1, ..., n$, and where Λ is the Markov-chain generator matrix. The Markov-chain generator matrix is given by $\Lambda = [\lambda_{ij}]$, where λ_{ij} is the rate at which the aggregation makes a transition from state i to j, and $\lambda_{ii} = -\sum_{j \neq i} \lambda_{ij}$ The long run probabilities, π of each state are given by the Markov steady state distribution, and $\pi = [\pi_0, \pi_1, ..., \pi_n]$. While smaller models can be constructed manually, software packages can be used to model and analyze larger and more complicated systems.

B. Model of the ISO *control signals*

The reliability of the V2G frequency regulation service is also dependent on the regulation requested by the *ISO*. Therefore, in this section we formulate a model to represent the *ISO* control signals.

Instructions from *ISO* to implement the AS occur on 4-second ticks and are delivered by *ISO* through approved telemetry. Response must happen by the following tick, and be verified by the one after that. The *ISO* control signals are normalized signals corresponding to the regulation capacity awarded. The regulation control signal sent by the *ISO* at any time t is denoted by z_t and $z_t \in Z, Z = [-1, 1]$. 1(-1) corresponds to maximum up (down) regulation that can be offered by the regulation service from the economic base point of the resource and 0 corresponds to no regulation[7].

To model the *ISO* control signals we first abstract out the time component of the signals. From here on, we drop the subscript t from our notation z_t.We then split Z into $2l$ bands, each of width $1/l$. All control signals that lie in the in the i^{th} band of Z are represented by the discrete state i in the set $R = \{1, .., 2l-1, 2l\}$. The model has been illustrated in Figure 2.The regulation r_i corresponding to the state i in R is assumed to be the average of the upper and lower regulations of the i^{th} band of Z, i.e.,

$$r_i = \frac{1}{2}((-1 + \frac{(i-1)}{2l}) + (-1 + \frac{i}{2l})) \quad (3)$$

Thus, we assume that if $z \in (\frac{(i-1)}{2l}, \frac{i}{2l})$, then the regulation requested by the *ISO* is r_i. Note that as l increases, the number of discrete states increase and the representation of the *ISO* control signal becomes more accurate.

We now compute the probability that regulation signal z is in the i^{th} band of Z. This probability is denoted by θ_i corresponds to the state i in R and can be computed the empirical cumulative probability distribution of the control signals $F_z(x)$

$$\begin{aligned} \theta_i &= p(z \in [-1 + \frac{(i-1)}{2l}, -1 + \frac{i}{2l}]) \\ &= \begin{cases} F_z(-1 + \frac{(i-1)}{2l}) - F_z(-1 + \frac{i}{2l}), \\ 0, otherwise \end{cases} \end{aligned} \quad (4)$$

$F_z(x)$ can be determined using historical data from *ISO*, can be determined. This distribution is based on the regulation signals received from the *ISO* in day. Under the assumption that there is no major power disruption event or a change in network configuration, this probability distribution holds for any given day.

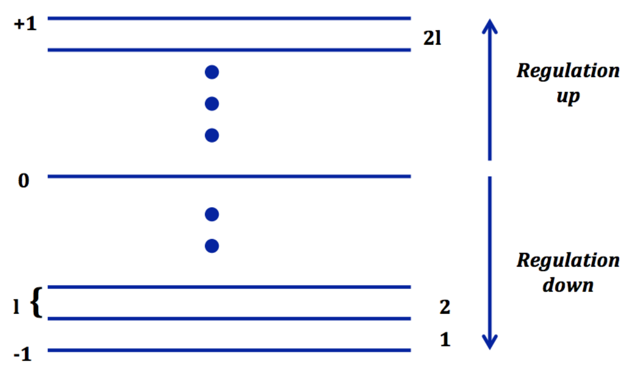

Fig. 2. Bands in *ISO* control signals and the corresponding discrete states

C. Reliability definition and assessment

In this paper, we define reliability of the *V2G* regulation resource as *the probability that aggregator can provide the regulation by the* ISO *when the* V2G *service is awarded a* *regulation capacity that is equal to the sum of the battery capacities of all the EVs enrolled in the aggregation by the* ISO.

To compute reliability, we merge aggregation and *ISO* regulation models and make use of the statistical independence of *ISO* control signals and availability of *EV*s in the aggregation to provide the regulation service. We adopt the following index notation:

k: index in S corresponding to the capacity in the aggregation available to provide V2G regulation services

j: index in R corresponding to regulation requested by *ISO*

The state space is the set of all the possible discrete states (c_k, r_j) and the probability of each state i is p_i, where

$$p_i = \pi_k \cdot \theta_j \tag{5}$$

A state i in the state space is considered as a failure state if for that state,

$$\begin{aligned} c_k &< +r_j, r_j > 0, \text{i.e, up regulation} \\ c_k &< -r_j, r_j < 0, \text{i.e, down regulation} \end{aligned} \tag{6}$$

Additionally, we can construct the set of indices of the failure

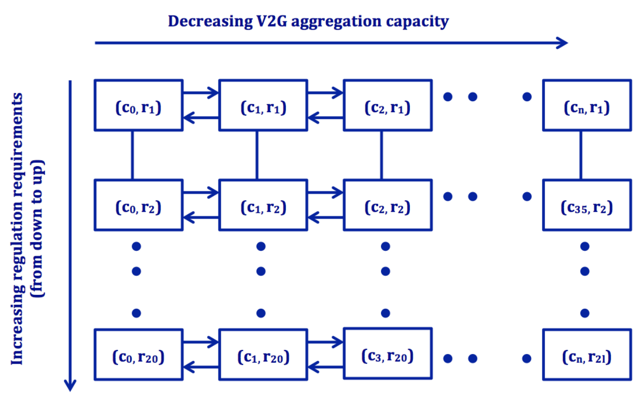

Fig. 3. State space of the reliability model

states $O = \{i : c_k < r_j\}$. The probability of system failure is then equal to the sum of the probabilities of the failure states, i.e,

$$P\{systemfailure\} = \sum_{i \in O} p_i \tag{7}$$

and

$$\begin{aligned} Reliability &= 1 - P\{systemfailure\} \\ &= 1 - \sum_{i \in O} p_i \end{aligned} \tag{8}$$

D. Sensitivity Analysis

The availability of an *EV* is dependent on the time of the day [4].For example, during noon, p is high, because *EV*s are generally parked at workplaces during this time. During evening hours, p is low since *EV*s are in use by owners to travel from work to home. Since we have abstracted the time component from *ISO* control signals, p cannot be determined with accuracy. In our work, we study the impact of parameter uncertainty on reliability through a sensitivity analysis of the reliability to availability p of an *EV*. Such a study is an important aspect of system reliability analysis. A method for calculating the analytical sensitivity has been described in [8]. However, in our work, we do a numerical sensitivity analysis of the reliability of the *V2G* frequency regulation service to the "availability" of the vehicles.

III. Experimental Results

In this section, we illustrate the framework proposed in the paper through a case study for the PJM market. The minimum performance score of a resource to be eligible to participate in the PJM's AS market is 75%.We consider a V2G aggregation of 40 *EV*s, with each *EV* having a battery of capacity 20 kW. This aggregation provides frequency regulation service to PJM. When all the *EV*s are present in the aggregation, the capacity available for frequency regulation is 800 kW. Since regulation resources with capacity less than 100 kW are not allowed to bid in the PJM AS market, we impose the constraint that five or more *EV*s are present in the aggregation at all times. We assume that there are no battery SOC constraints on any of the *EV*s, i.e., if an *EV* is present in the aggregation, it is able to offer its full battery capacity for provision of frequency regulation in both the directions. Thus, the aggregation at any time, can be in anyone of the 36 capacity states, represented by the by set $S = \{0, 1, 2, ..., 35\}$

To model the frequency regulation signals, we use historic dynamic regulation data from PJM available for May 2014. We divide the control signals into 20 discrete states represented by the set $R = \{-10, -9, .., 9, 10\}$ with corresponding regulation capacities (in kW) as $C = \{-760, -680, -600....680, 760\}$ The cumulative probability distribution function for the regulation data is plotted in Figure 4.The probability of any state $i \in R$ is calculated from the cumulative distribution function using equation 4

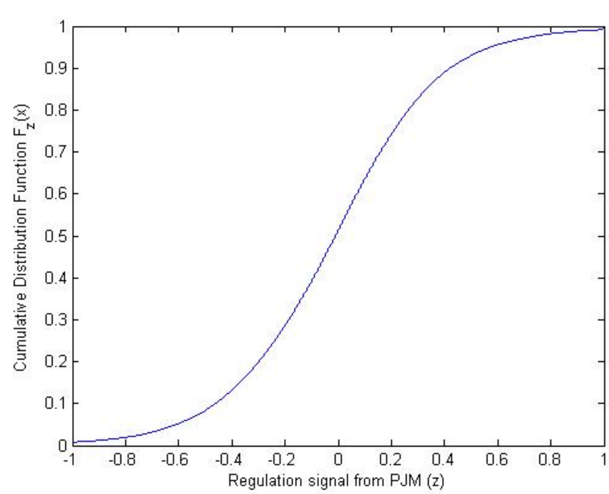

Fig. 4. Cumulative Distribution Function of the frequency regulation control signals from PJM

To perform the reliability analysis, we use data from [5] and assume *EV* availability to be 90%. We note from equation 1,

$$\frac{\lambda}{\mu} = \frac{p}{1-p} \tag{9}$$

The failure is assumed to be 0.1 *EV*/hr and therefore, from equation 9 the repair rate equals 0.9 *EV*/hr. Using these rates, we create a Markov chain for the aggregation which takes values in the set S and compute the steady state distribution vector $\pi = [\pi_0, \pi_1, ..., \pi_{35}]$. Next, we form the state space consisting of 35×20 states and compute the reliability as described in Section II. The reliability of the *V2G* service for the given aggregation is 95.28%, which is greater than 75%

Next, we perform a numerical sensitivity analysis of the reliability to the "availability" of the *EV*s. We assume that the availability of each *EV* varies from 25% to 95%. The reliability of the *V2G* service with respect to the availability has been plotted in Figure 5.

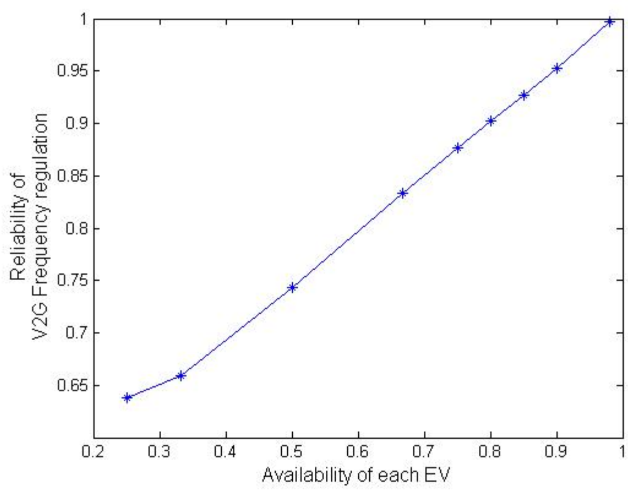

Fig. 5. Sensitivity of Reliability of *V2G* regulation service to availability of an *EV*

IV. Concluding Remarks

A Markov model to study the reliability of *V2G* service has been formulated and the sensitivity of the reliability to the availability of *EV*s has been studied. We note that even for a small fleet of vehicles (about 40 *EV*s), the reliability of the *V2G* service is very high. We also note that the aggregator can relax mobility constraints on *EV*s without significantly affecting the reliability of the service. Such analytical results can help promote the wide-scale deployment of *V2G* framework for provision of frequency regulation.

V. Future Work

The study of the reliability of the *V2G* service provided by a dynamic aggregation of *EV*s with different battery capacities under battery state of charge (soc) constraints is left to future work. The work can also include common cause failures owing to reasons such as failure in telemetry.

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