V2G Electric Power Capacity Estimation and Ancillary Service Market Evaluation

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Abstract-- **Sharing power assets between transportation and power system is the focus of V2G that can create a compelling new economics. Projected V2G penetration levels across utility customers are a promising clue that V2G may dominate the market in the near future. This will herald evolution of V2G parking lots. This paper describes mathematical model for estimating the electric power capacity of a V2G parking lot system. The electric vehicle demand/supply model was formulated as a queuing theory problem, exhibiting stochastic characteristics. This paper addresses the modeling of V2G power demand and supply as well as evaluation of its electricity market potentials. Promising simulation results are gained leading to a claim that V2G electric power capacity can be substantial with attractive ancillary services revenue opportunities. The proposed model was tested using Tesla Roadster EV and PHEV versions. Results could be useful for power system software developers seeking base case data capacity estimation of V2G parking lots. An expression for grid gain factor was developed, and analysis showed that 40.3% optimal gain factor is obtainable.**

***Index Terms*-- Microgrid, Power market, Queuing theory, Stochastic modeling, V2G.**

I. NOMENCLATURE

V2Gs	Vehicle-to-grid Technology
EV	Electric Vehicle
DER	Distributed energy resource
BEV	Battery Electric Vehicle
CAISO	California Independent System Operator
E	Economic values of V2G
λ	Mean rate of V2G arrivals
μ	Mean rate of V2G departure
$p(n)$	probability that there is n V2Gs
N	Maximum number of V2Gs at a bus
$N_{samples}$	Number of simulation samples
n	Any number of V2Gs
n_{imp}	Number of vehicles importing power
n_{exp}	Number of vehicle in exporting power
i	i^{th} count of V2G
r	Randomly generated numbers- range: 0 to 1
α	Battery charging constant
β	Battery discharging constant
$P_{base\,load}$	Base load power
$P_{EV,dem}$	Power demand for charging n V2Gs
$P_{EV,max}$	Maximum battery capacity of a V2G
$P_{EV,0}$	Initial charge of battery
P_{EV}	Instantaneous charging power in battery
t	Time for charging
t_{max}	Maximum charging time
$t_{exp,i}$	Time for i^{th} V2G to export power
t_{ci}	Time for i^{th} V2G to import power
t_{exp}	Time required discharging battery
t_s	Service time
$P_{EV\text{-}discharge}$	Instantaneous discharge power in battery
$P_{EV\text{-}exp}$	Power exported from V2G to grid
$P_{EV,0\_i}$	Initial power for the i^{th} V2G
$P_{EV\text{-}net}$	Net power flow from V2G to grid

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II. INTRODUCTION

THE electrical distribution systems are expected to undergo radical changes with the penetration of distributed generators and V2G facilities [1], [2],], [3], [4], [5], [6], [9]. This is aided by the inter-governmental Kyoto Protocol environmental concerns [7] and US government's energy policies towards more reliable, economic, secured and efficient operation of US national electric grid [6]. In a bid to reinforce electric power generation through diversification of resources, global interest is shifting from conventional generators to renewable energies and DER. Several researchers have addressed the area of integrating distributed generators into the electric distribution system [2], [3], [4], [5]. The fact that vehicles (including V2Gs) are commonly used for about 4.1% time of the day (and in the rest of the time, parked at homes and offices) one can place V2G as a DER with a potential solution to research on advanced electricity storage technologies [8]. Although the availability of any one vehicle is highly unpredictable, it becomes a great resource to reckon with when thousands of vehicles are available. A V2G facility may provide power to help balance loads by "valley filling" (charging at night when demand is low) and "peak shaving" (sending power back to the grid when demand is high) as well as enable utilities to have new ways to provide regulation services (keeping voltage and frequency stable) and provide spinning reserves (meet sudden demands for power) [9], [10], [17]. The V2G units could be a key enabling new load that supports a cleaner, more renewable, and lower-carbon grid. Hence, there is justification to the growing research activities among car companies, national government and electric utilities [11],[12]- all motivated towards exploring the potentials of V2G technology and other DERs.

V2Gs have been used for stabilizing the grid operations [9], [10], [13], [14], [16] and its capacity and market potentials [9], [15]. Saber, A.Y et al [15] used optimization technique to formulate an intelligent scheduling strategy in a parking lot. It is suggested in [10], [18] that V2G is a near-future resource to reinforce renewable power sources such as wind power by storing excess energy produced during windy periods and providing it back to the grid during high load periods. However, the potential challenges to V2G regime are limitations in battery technology, cost, weight as well as issues of additional wear and tear on the battery [19].

The V2G development is still in an infant stage thereby creating limitations whereas measurements are required in real-life systems. Another issue is that in a typical V2G parking lot system, vehicles at different states of charge could be arriving for either charging their vehicles (load) or discharging to export power to the grid. Whereas these activities are taking place at different times, the research community faces a difficult issue: what is the capacity of a V2G parking lot to use in a power system analysis? One way to approach this problem is to deal with V2G parking lot capacity in terms of percentage penetration [20]. Therefore, the main objective of this paper is to investigate V2G parking lot electric power capacity and then explore its ancillary service potential in a deregulated power market environment. This approach will be useful in a loadflow analysis where a V2G-based bus may exist.

The motivation for this research came from the pioneer work done by R. Gracia-Valle et al [21] in which electric vehicle demand system was modeled as a queuing theory problem, exhibiting stochastic characteristics. The model needs to be extended further into power system domain to include the following issues: (a) The power export to the grid, (b) a mix of charging and discharging operations in a typical car parking lot, (3) V2G parking lot energy market operations. This paper attempts to extend the fundamental work of R. Gracia-Valle et al to reflect these identified opportunities.

This paper is organized as follows:- In section III, the V2G system is modeled under three scenarios: (a) V2G system demand model, (b) V2G system supply model, and (c) Heterogeneous car pool system. In this section, the baseload and power capacity of a typical parking lot are modeled. In section IV, the economic value of V2G parking lot is analysed considering four ancillary services: baseload, peakload, spinning and regulation. Section IV presents the study results using different case studies; conclusions are presented in section VI.

III. Modeling of V2G Systems

A. *V2G System Demand Model* [21]

As seen in Fig.1, the arrival of V2Gs (customers) in a parking lot can be modeled as essentially a storage process, being served by the servers (charger/inverter interface). Customers may arrive one by one, or in batches (we assume that the inter-arrival times are independent). This behavior of the V2G parking lot system classifies it as a queuing theory problem. Hence, the PQ bus demand model shall be a stochastic process.

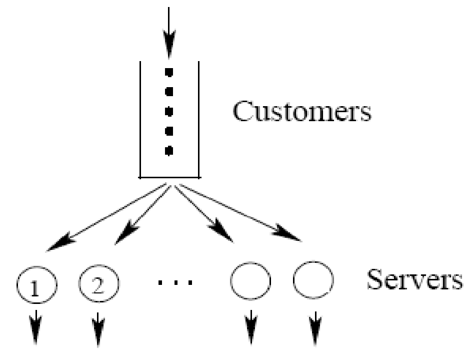

Fig. 1: Arrival of V2Gs (customers) in its parking lot with Charger/inverter interface (servers) [28]

The battery of a Tesla Roadster EV (in a charging mode) was modeled as an exponential function of time [21]. Thus for any given time, t, the instantaneous charging status is [21]:

$$P_{EV} = P_{EV,\max}\left\{1-e^{-\left(\alpha . t/t_{\max}\right)}\right\}+P_{EV,0} \quad (1)$$

Where the value of the constant α of the battery was 6.9077. For a full battery charge, we have:

$$P_{EV} = P_{EV,\max} \quad (2)$$

Substituting (2) into (1) and solving for the initial battery charge yields:

$$P_{EV,0} = P_{EV,\max} . e^{-\alpha t / t_{\max}} \quad (3)$$

The instantaneous charging status of the BEV considering different initial power status is as shown in Fig. 2.

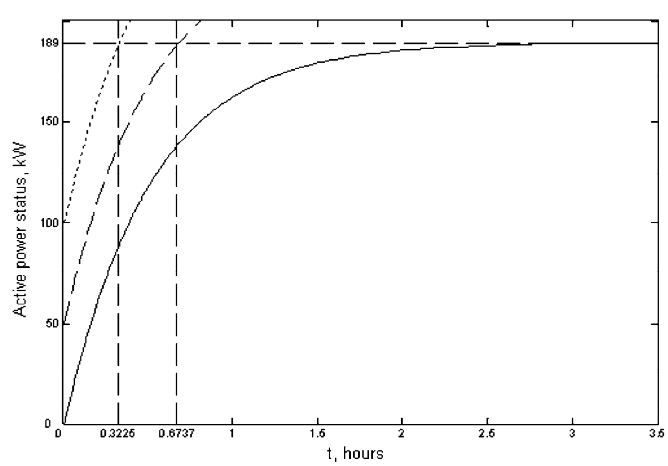

Fig.2: Instantaneous charging status of Tesla Roadster EV [21]

The power demand for charging EV is given by:

$$P_{EV,dem} = P_{EV,\max} - P_{EV,0} \tag{4}$$

Substituting (3) into (4) gives the power demand of a Tesla Roadster to be fully charged (Fig. 3), thus we have:

$$P_{EV,dem} = P_{EV,\max}\left\{1 - e^{-\left(\alpha.\frac{t}{t_{\max}}\right)}\right\} \tag{5}$$

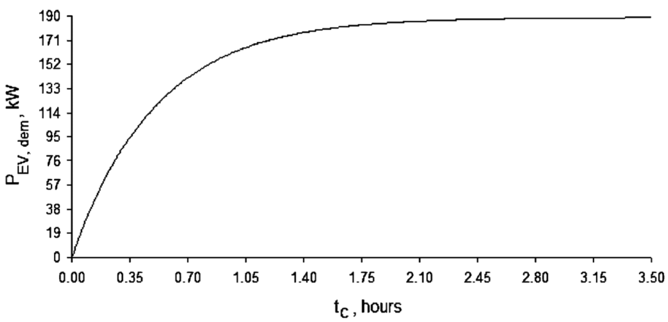

Fig.3: Power demand of a Tesla Roadster EV to be fully charged [21]

Assuming that the 50% high penetration of V2G predicted for the future market in [29] will have five different types of batteries of different charging rates, α_i, then for n-V2G system requiring time, t_{ci} for charging an i^{th} vehicle i, the total power demand for charging the whole system is:

$$P_{EV,dem} = P_{EV,\max}\left\{n - \sum_{i=1}^{n} e^{-\left(\alpha_i \frac{t_{ci}}{t_{\max}}\right)}\right\} \tag{6}$$

Based on the expected variety of batteries in future V2G market, we assumed the following charging and discharge rates as shown in the table below (Table 1).

Table1: Charging and Discharge rates for various V2G

V2G Vehicle Types	Battery Characteristics	
	α	β
Type-1	6.9077 [14]	5.9077
Type-2	7.9077	6.9077
Type-3	8.9077	7.9077
Type-4	9.9077	8.9077
Type-5	10.9077	9.9077

For n = 1, and assuming the data in Table 1, we see in Fig. 4, the effect of α on the predicted power demand profile. As α increases, the battery charging rise time increases. As improvements take place in the manufacture of batteries with high charging rate, such batteries will definitely boost the V2G market.

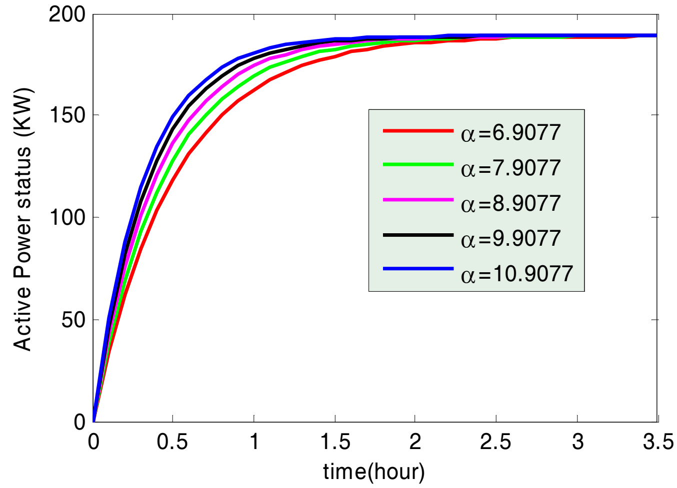

Fig. 4: Power demand of a V2G to be fully charged for any α

The probability $p(n)$ that there is n-V2G vehicles under charging at a typical load bus (assuming that mean rate of V2G arrivals equals mean rate of V2G departure) is given by [21]:

$$p(n) \approx \frac{1/n!}{\sum_{i=0}^{N-1}\left(\frac{1}{i!}\right) + \frac{1}{\left(1-\frac{1}{N}\right).N!}} \tag{7}$$

$$Where \quad n = 0,1,2,3,4,\ldots\ldots,N$$

Adopting the procedure described in [21] for M/M/N queue system, a stream of random numbers between 0 and 1 (r [0,1]) is generated, and set as n the lowest value among the set of values [0, 1, 2, …..,N] which satisfies the inequality:

$$r[0,1] > p(n) \tag{8}$$

The charging service time required by the i^{th} V2G vehicle is computed as [14]:

$$t_{ci} = \begin{cases} t_{\max}, & if \;\; r(0,1] < \mu.N.e^{-\mu.N.t_{\max}} \\ -\frac{1}{\mu.N}.Log_e\left(\frac{r(0,1]}{\mu.N}\right), & if \;\; r(0,1] \geq \mu.N.e^{-\mu.N.t_{\max}} \end{cases} \tag{9}$$

With equations (9) and (6), we can compute a sample of the power demand for n-V2G parking lot. A stochastic base load estimate for n-EV system was evaluated for N-samples using the expression:

$$P_{base\,load} = \frac{\sum_{i=1}^{N_{samples}}\left\{P_{EV,demand}(i)\right\}}{N_{samples}} \tag{10}$$

The base load computed in [21] for 10,000 samples of n-EV system is as shown Fig. 5.

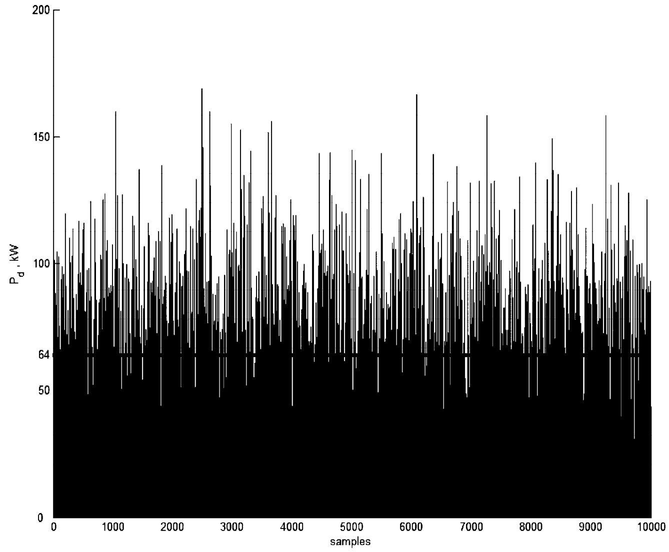

Fig. 5: Basic load of n-EV system for 10000 samples [21]

This power demand from the grid may be relieved by using a renewable energy-sustained docking facility, such as the one reported earlier in [23].

B. V2G Power Supply Model

In this section, the foundation of work in [21] is extended, by considering power export to the distribution network. Although Tesla Roadstars EV used in [21] is a BEV, a hybrid version suitable for V2G is assumed in this research. If for any reason the V2G battery was completely discharged (this is not recommended as it impairs battery performance), the owner can drive off from parking lot on an engine-drive mode. Shallow cycling of batteries has less impact on battery lifetime than deep cycling [24]. In this research, we assumed a battery discharge limit of 0.2kW, enough to drive the EV in Electric mode if engine cannot start. This limit is considered appropriate since a typical EV may use 0.44 kWh/mile [27] when commuting. Hence, 0.2kW is expected enough to drive the vehicle to a maintenance shop, if needed.

In this section, the V2G discharge into the distribution system is modeled as a decay function over time. The battery instantaneous discharging status is given by:

$$P_{EV-discharge}(t) = P_{EV,0}.e^{-\beta.t/t_{max}} - 0.2 \quad (11)$$

At $P_{EV\text{-discharge}} = 0$ for various β as defined in Table1, we establish (as shown in Fig.6) the time t_{exp} in hrs required to discharge battery from P_{EV_0} to the battery discharge limit. As seen, the time required for such a discharge reduces as β increases (at constant load).

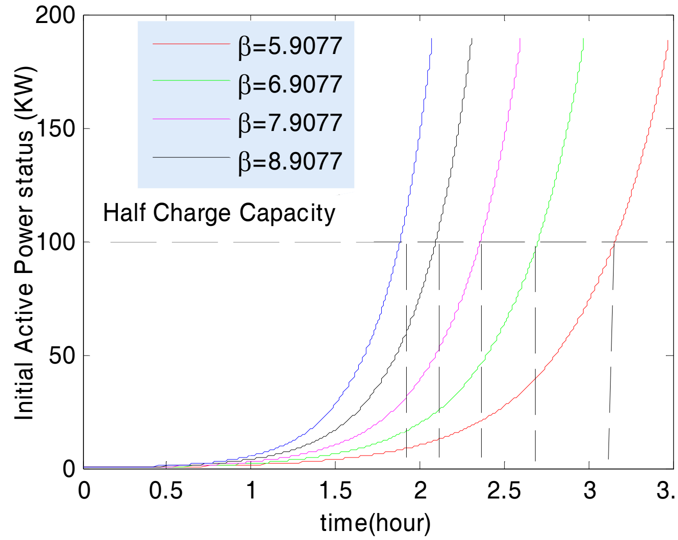

Fig. 6: Time to discharge V2G from Initial Status to 0.2kW

Hence, the power discharged at any given time from an initial battery power status is as shown in Fig. 7 and modeled as:

$$P_{EV,\exp}(t) = P_{EV,0} - P_{EV,0}.e^{-\beta.t_{\exp}/t_{\max}} \quad (12)$$

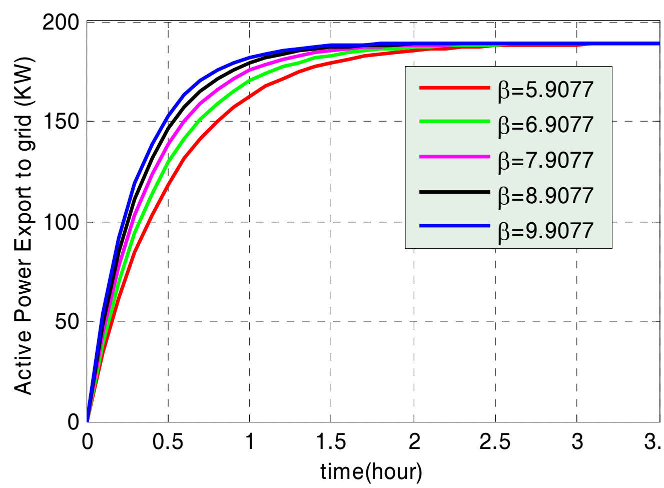

Fig. 7: Active power export to grid from a V2G vehicle.

In real life, an initial battery power status is stochastic in nature, and shall be determined using the method similar to that used to determine t_{ci}. Hence, for n_{exp} V2Gs in discharge mode, the initial power for the i^{th} V2G vehicle is computed from:

$$P_{EV,0\_i} = \begin{cases} P_{EV,\max}, & if \;\; r(0,1) < \mu.N.e^{-\mu.N.t_{\max}} \\ & if \left[-\dfrac{3n.P_{EV,\max}}{\mu.N}.\zeta \right] > P_{EV,0\_i} \\ -\dfrac{3n.P_{EV,\max}}{\mu.N}.\zeta, & if \;\; r(0,1) \geq \mu.N.e^{-\mu.N.t_{\max}} \end{cases} \quad 13$$

Where:

$$P_{EV,0\_i} = \begin{bmatrix} P_{EV,0\_1} \\ P_{EV,0\_2} \\ \vdots \\ P_{EV,0\_n_{\exp}} \end{bmatrix} \quad (14)$$

$$\zeta = Log_e\left(\frac{r(0,1]}{\mu.N}\right) \quad (15)$$

$$N = n_{exp} + n_{imp} \quad (16)$$

The total power exported to the distribution system for n_{exp} number of V2Gs will be:

$$P_{EV-\exp}(t) = \sum_{i=1}^{n_{\exp}} P_{EV,0\_i}\left(1-e^{-\Delta}\right) \quad (17)$$

Where:

$$\Delta = \beta_i t_{\exp,i} / t_{\max}$$

C. Heterogeneous Car Parking Lot

In a real life scenario, some V2Gs will be in a charging mode while others will be in discharging mode. The net power flow in a parking lot mix of n_{imp} number of power-importing V2Gs and n_{exp} number of power-exporting V2Gs is:

$$P_{EV-net} = P_{EV-\exp} - P_{EV,dem} \quad (18)$$

From eqns (6) and (18), we obtain the model for net power export to grid as:

$$P_{EV-net} = \left\{ \sum_{i=1}^{n_{\exp}} P_{EV0\_i}\left(1-e^{-\Delta}\right) - P_{EV,\max}\left(n_{imp} - \sum_{i=1}^{n_{imp}} e^{-\Delta'}\right)\right\} \quad (19)$$

Where,

$$\Delta' = \alpha_i \times t_{ci} / t_{\max}$$

In the power discharging mode, a power electronic inverter interface can be designed to provide reactive power to the distribution system for reactive power compensation and voltage regulation [25].

A scenario may arise during which net power to the grid is zero (i.e., power demand and power discharged are same). Hence from eqn. (19), we have eqn. (20) as follows:

$$\frac{\sum_{i=1}^{n_{\exp}} P_{EV0\_i}\left(1-e^{-\Delta}\right)}{P_{EV,\max}} = n_{imp} - \sum_{i=1}^{n_{imp}} e^{-\Delta'} \quad (20)$$

Dividing both sides of eqn (20) by n_{exp} V2Gs makes the numerator of the LHS the average V2G power exported to the grid:

$$\frac{\sum_{i=1}^{n_{\exp}} P_{EV0\_i}\left(1-e^{-\Delta}\right)}{n_{\exp} \times P_{EV,\max}} = \frac{1}{n_{\exp}}\left(n_{imp} - \sum_{i=1}^{n_{imp}} e^{-\Delta'}\right) \quad (21)$$

The term on the LHS of eqn. (21) is a measure of average power discharged to the grid per vehicle, and shall be called the *Gain factor,* G, defined as:

$$G = \frac{\sum_{i=1}^{n_{\exp}} P_{EV0\_i}\left(1-e^{-\beta_i t_{\exp,i}/t_{\max}}\right)}{n_{imp} \times P_{EV,\max}} \quad (22)$$

The relationship between G and β is as shown in Fig.8. An optimal grid gain factor (in this scenario) is about 0.403 (i.e., average of 40.3% of the V2G maximum battery power goes to the grid). The optimal β is about 8.0.

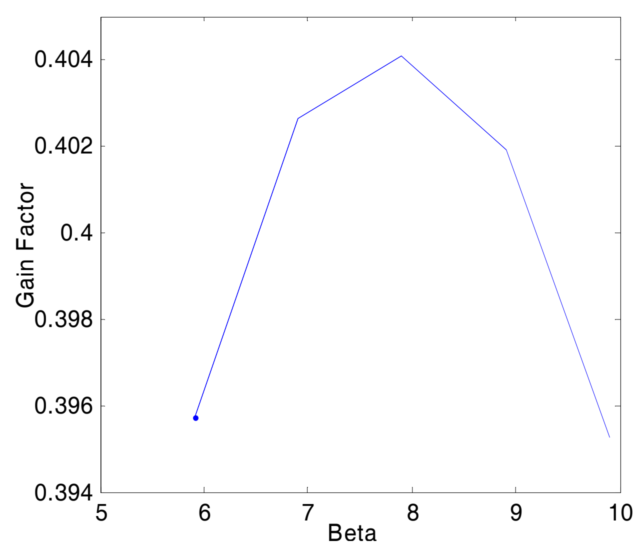

Fig. 8: Gain Factor versus beta (β)

IV. ECONOMIC VALUE OF V2G

The V2G facility provides power to help balance loads by "valley filling" (charging at night when demand is low) and "peak shaving" (sending power back to the grid when demand is high), as well as enable utilities have new ways to provide regulation services (keeping voltage and frequency stable) and provide spinning reserves (meet sudden demands for power) [9],[10]. All these ancillary services constitute the economic values of V2G, mathematically defined as [9], [10]:

$$E = \text{Revenue} - Cost \quad (23)$$

A. Revenue Market Operation

According to Kempton et al [3], V2G revenue depends on the market scenario that V2G power finds itself. For markets that deal with electricity energy as a commodity, the base load and peak load scenarios are computed as:

$$R = \rho'.P'.t' \quad (24)$$

Where:

R=Revenue ($)

ρ′=market rate for electricity sale ($/KWh)

P′=Exported power (KW)

t′=Total time Power is exported (hrs)

For spinning reserves and regulation services, revenue is defined as [10]:

$$R = \rho'.P'.t' + \rho''.\gamma.P''.t'' \quad (25)$$

Where,

ρ″=Capacity Price ($/KW-h)

P″=Contracted Power Capacity (KW)

t″=Contracted duration (hrs)

γ= percentage regulation time

Note that the capacity price unit, $/kW-h, means $ per kW capacity available during 1hr —whether used or not—whereas energy price unit, $/kWh means $ per kWh.

Balancing supply and demand to maintain 60 Hz operation is a complex and difficult task given today's grid with its little energy storage capacity. The utility balances generation and load to maintain frequency balance. For example, PJM (a regional transmission organization that manages the high-voltage electric grid and the wholesale electricity market that serves 13 states and the District of Columbia) commonly pings generators to control regulation as often as hundreds of times per day. Hence, while regulation services requires several dispatches per day, spinning reserve services about 20 dispatches in a year- typically dispatch time is 10mins long. For regulation, revenue estimate is given by [10]:

$$R = \rho'.P.t_s + \rho''.\gamma.P.t_s \quad (26)$$

B. Cost Market Operation

A detailed cost analysis of V2G was reported in [10], in which cost was computed from purchased energy, wear and capital costs. In this research, we shall use the costs computed in [3] (reported in per V2G per annum). If average cost of operating a V2G is *C,* then total cost for n_{exp} vehicles is:

$$Cost_{tot} = n_{exp}.C \quad (27)$$

V. Numerical Results

A. Case Study-I: V2G demand model

The V2G System demand algorithm discussed in section III was tested using the parameters used in [21]: t_{max} = 3.5 hrs, $P_{EV,max}$ = 189kW, N = 10, μ=8, N_{sample} = 10,000 in addition to the data in Table1. The simulation result is as shown in Fig. 9. The estimated base load is 66.2320KW, and shall be the real power P demand at given PQ bus for loadflow analysis.

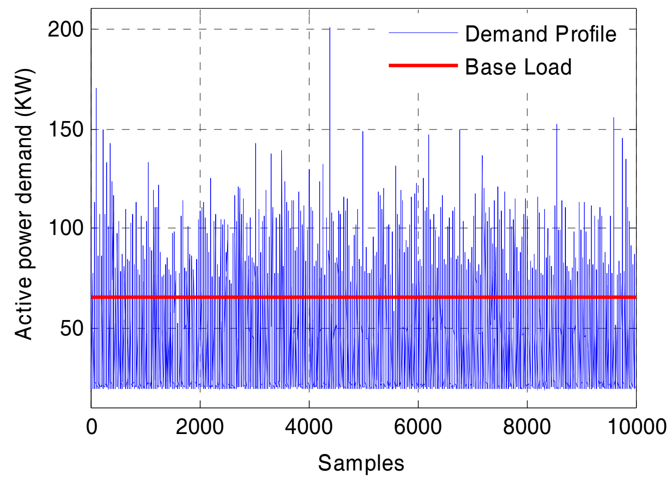

Fig. 9: Base load for n-EV System of 10,000 samples

B. Case Study-II: V2G supply model

Using eqn 17, the stochastic estimation of the V2G power supply capacity for n-V2G system was found to be 341.73kW (Fig. 10).

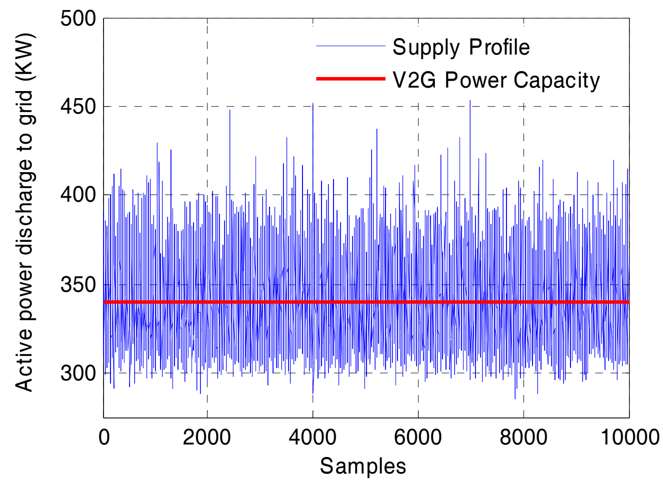

Fig. 10: Power Capacity for n-V2G System (10000 samples)

C. Case Study-III: V2G Heterogeneous Parking Lot

Simulation of (19) showed a net power capacity of 275.503KW (difference between V2G power demand and power supply for a parking lot), and this is shown in Fig. 11.

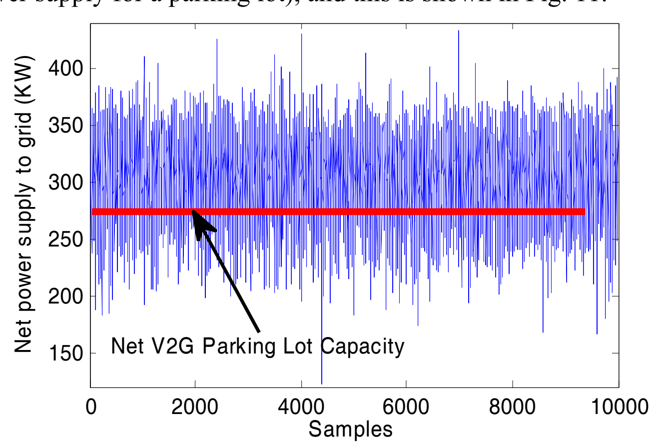

Fig. 11: Net Power capacity for n-V2G System (10^4 samples)

D. Case Study IV: Economic Value of V2G

To investigate the economic value of a V2G parking lot, it is assumed that the parking lots are installed to a feeder (Fig. 12). The hour demand curve of such feeder will be useful in calculating the economic value. A feeder demand curve in [25] is scaled down by 10% and adapted in this research (Fig. 13).

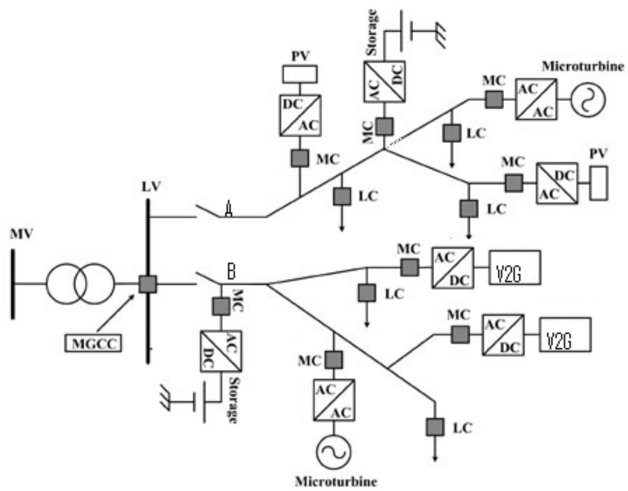

Fig. 12: Microgrid Architecture [26]

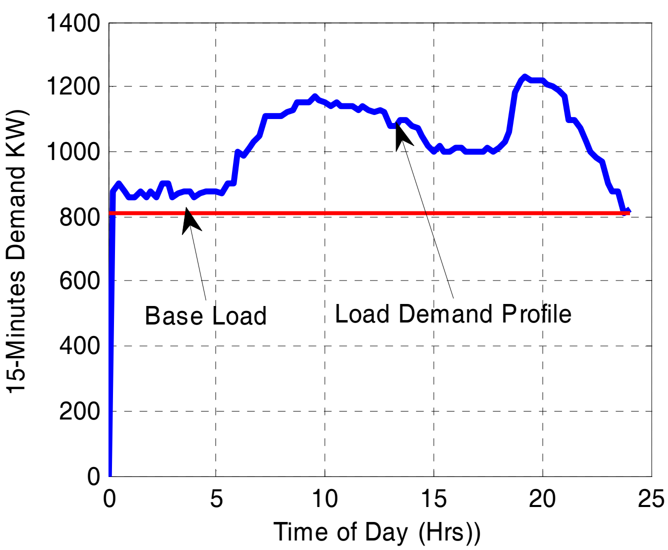

Fig. 13: Hrs Demand Curve (adapted from) [15]

The economic values of V2G for four different ancillary services were computed using the data presented in [10]. For base load calculations, eqn 24 was applied; the following data was used: $\rho' = 0.1$\$/kWh, P'=275.503kW, t'=96% of 24hrs [8] for a year (since vehicle sits idle for about 96% of the day. However, this work assumes further that V2G shall be available at the parking lot only during the day- hence, we use $t' = 0.96 \times 12 \times 364$ hrs for a whole year; for peak load operations (eqn.(24)), the following were used: ρ' =0.3\$/kWh, P'=275.503kW, t'= service periods for the peak load (being 9am-2pm and 7pm-10pm (from Fig. 13). Also for spinning reserve operation, eqn (25) was used; the appropriate data are: $\rho' =$ 0.003\$/kWh, ρ'' =0.007\$/kWh, $P' = P'' =$ 275.503kW, and contracted time $t' = t''$ =10mins duration (we use 20 dispatches per year for each 10mins duration as suggested in [10]). Finally, for regulation operations (eqn. (23)), ρ'=0.004\$/kWh, ρ'' =0.1\$/kWh, P=275.503kW, and the service time $t_s =$ 13.33hrs (Since [10] reported typical dispatch of regulation services at about 400 times per day, each of few minutes duration. We assumed 2mins duration in this work, hence requiring 13.33hrs per day). For all computations, the value of percentage regulation λ is given as 0.1. According to data from [10], the average cost of operating a V2G for spinning reserve is \$438/annum, regulation \$2374/annum, and peak load \$1210/annum. However, because of high level of operational cost as well as maintenance cost expected for base load operation, \$4000/annum was used. While eqn (23), eqn (24) and eqn (25) were used to calculate the revenue, the average cost of operating the V2G was used in eqn (27) to calculate the total cost incurred in operating the V2G system. With the revenues and total cost known, we computed eqn (23) for the economic value.

The annualized results are as shown in Fig. 14. The results show that using the V2G for peakload and regulation services have more economic value than when used for other ancillary services. The result also indicate that it is unprofitable to use the V2G in the considered power market (CAISO market operation was utilized) as a spinning reserve. Although the market analysis in this research encourages peak load operation, [10] pointed out that choice of ancillary service application depends on the type of V2G. For instance, it was proposed to be a fuel cell based V2G for peak power operation; BEVs for regulation and spinning operations. It is also expected that electricity markets will always affect the V2G economic value.

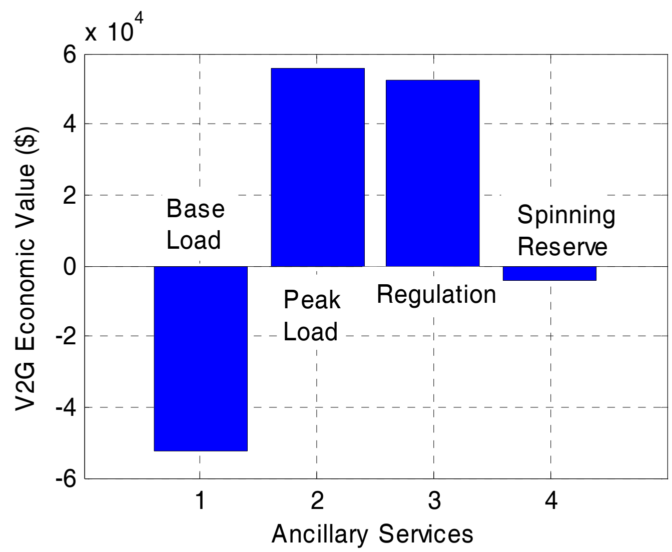

Fig. 14: V2G Annual Profit for Different Ancillary Services

VI. CONCLUSIONS

This paper investigated a V2G parking lot system in which vehicles at different power status (state of charge) arrive at random times for either charging a vehicle or discharging power to the grid. Existing mathematical model was extended to answer the question: what power capacity is available in a

V2G parking lot facility? The approach used to solve this problem was based on the pioneer work of R. Gracia et al [21]. In this paper, the electric vehicle demand/supply system was modeled as a queuing theory problem with stochastic properties. Mathematical model for grid gain factor was developed, and simulation result showed that 0.403 optimal gain factor could be obtained. The V2G power market potentials were also explored. It appears from the simulation results that the V2G parking lot facility can have a substantial electric power as well as attractive revenue capability. The results also show that using V2G for peakload and regulation services can be more attractive than other ancillary services.

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