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# Techno-Economic Aspects in Electricity Market Operations with Grid Interfaced Electric Vehicles

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*The focus of this paper is to explore the oppor- tunities and challenges associated with grid-interfaced electric vehicles in the view of growing electrification of the transporta- tion sector. The study covers the following key concerns, 1) the configuration for electric vehicle (EV) – electric utility interfacing, 2) potentiality of EVs for grid services in competitive market environment, and 3) evaluation of charging/discharging impacts of a large deployment of EVs on the grid. The study suggests that the three principal participants, the power utilities, the vehicle owners, and the entity called aggregator can proactively work together to better manage the charging demand by the EVs, preventing the negative impacts caused by the uncontrolled charging. Simulative analyses are also presented to highlight the impact of grid-to-vehicle (G2V) and vehicle-to-grid (V2G) on the demand profile and electricity market price. The development of G2V/V2G profiles for grid services would require taking into consideration the vehicles' heterogeneity which is dependent upon mobility behavior. The prospect of drawing revenue by offering energy and capacity services through V2G in volatile ancillary services market can also offset the barrier of expensiveness in their adoption, in addition to improving the grid reliability.*

*Index Terms: Electric vehicle, electricity market, grid-to- vehicle (G2V), vehicle-to-grid (V2G), ancillary services.*

## 1.0 INTRODUCTION

While the advent of energy efficient electricity powered Electric Vehicles (EVs) alleviates the problem of $CO_2$ emission and fossil fuel consumption, it crafts a new problem of grid anxiety to the power sector. As it seems, the challenge is to prepare the existing power network to cope up with the excess load of the EVs. Although, the problem is not so simple but multifaceted, right from handling the additional load to working out the electricity market business framework for the participation of EVs. The three segments of power system face costly infrastructure upgrades as, apart from the distribution capacity (substations, transformers, feeders, protective devices) enhancement, transmission and generation capacity addition will be vital to meet the increased load from EV charging stations. The socioeconomic competence may even lead to clustering effect, confining EVs adoption to certain sections of society (probably high-income group). This put up locational aspect challenge to the utilities as multiple EVs charging from the same transformer could overload a few distribution transformers more while others less. Further, the simultaneous charging of EVs at a time would generate a peak EV load which, depending upon the user driving/arrival pattern, may coincide with systems peak creating a worst-case scenario to control the grid. With the right coordination of charging/discharging modes,

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EVs could serve as a controllable resource to the grid, exploit- ing their fast response capabilities (ramp up and ramp down) to maintain demand-supply balance. Thus, the EVs provide a convenience (to an extent) to operate it in vehicle-to-grid (V2G) mode [1]–[5] by regulating the charging/discharging process, thereby an opportunity to sold power back to the grid as a storage device during the times of peak demand. This process is termed as intelligent charging based upon which EVs are by now researched rationally as a proxy to some expensive conventional generation to provide a few ancillary services.

There arises a lot of utility and regulators concerns to make intelligent engagement of EV resource for grid services possible. First, to relieve the grid from peak load impact, a tariff system providing incentives to the customers for off- peak charging such as time-of-use rate (TOU) system offering flexible charging rates is needed. Next, intelligent meters will be required to segregated the transportation consumption (usage in EV charging) from rest of the energy usage like residential, commercial consumption. This justifies the place of advanced metering infrastructure (AMI) for building a smart network where indeed the demand response is achieved by means of intelligent EV charging. Location monitoring of the vehicle to track and bill the exact customer will be its part. Finally, the business models for installation and governing of charging stations are to be instituted. Some private parties may be ready to build and operate the charging networks. The role of the utility company and charging network provider over the ownership, operation, and management of the network have to be worked out for smooth operation. This requires intel- ligent tweaking of rules pertaining to regulation, inspection, compliance, permission etc. to encourage third parties entry into the power market via healthy competition. Alongside utility concerns, at each step economic viability study from EV owners perspective will be needed as high EV cost, charging point availability, charging time, range anxiety, costly domestic charging infrastructure etc. are presently the potential barriers to its adoption. Hence, interfacing electric vehicles (EV) with the power grid would influence the four major segments of electricity market namely, 1) power system energy, 2) power system capacity, 3) ancillary services, and 4) transmission and congestion management in different ways.

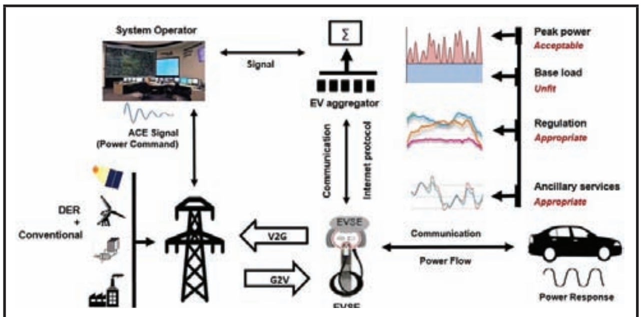


FIG. 1. COLLABORATIVE VEHICLE – UTILITY INTERFACE IN THE SMART GRID FRAMEWORK

The subsequent sections of the paper are comprised as following. To manage the new EV load, charging manage- ment solution integrating the utilities and EV owners will be vital. The framework for which is discussed in Section II. The impact of G2V/V2G modes of operation, i.e. the charge/discharge profiles created by the large pool of EVs, on the grid load and hourly market price are examined in Section III. The smart operation of above two modes requires the selection of electrical parameters based on mobility behavior of customers, for which the relevant features are detailed in Section IV. Finally, paper is concluded in Section V discussing the essential steps to enable integration of EVs into the grid.

## 2.0 ELECTRIC VEHICLE AND POWER UTILITIES INTERACTIONS

In order to facilitate EVs participation in electricity market to provide load/generation services via intelligent charging (G2V/V2G modes), integrated control at system operator level is vital. Fig. 1 shows the illustration of the key participants and possible paths for the movement of energy and communica- tion/control signals in an EV interfaced structure. The aggre- gator is a proposed entity [1], [6] responsible for controlling and providing interface of large pool of EVs representing a capacity in the range of MWs to the system operator. The presence of the aggregator is central to the architecture as it appears futile (also impractical) to individually communicate a capacity of few kW (of individual EVs) incapable of influenc- ing the grid at MW level to the system operator. The swift response capabilities (ramp up and ramp down) combined with adequate availability during long parking periods make the aggregator controlled large deployment of EVs a good asset for energy and capacity services in the volatile high value power markets like regulation, spinning reserves, etc., as depicted in Fig. 1. Based on this, [2] formulated the computations for revenue and cost components in providing V2G to the power markets namely, peak power, regulation and spinning reserves. The electric vehicle supply equipment (EVSE) is supposed to encompass metering and bidirectional communication interface to communicate with the aggregator along with grid connection for power transfers. Also, a large- scale deployment of EVs as a storage service provider could allow utilities to integrate more intermittent renewable energy sources avoiding conventional generation capacity addition as proposed in [3]. The fast control capability could further help in easing out their intermittency [7].

## 3.0 GRID LEVEL IMPACTS OF ELECTRIC VEHICLES

The energy and capacity component of the electricity grid is directly affected by the introduction of EVs in the market. The EV characteristics such as EV type, battery capacity, en- ergy consumption; the mobility behavior, viz. driven mileage, arrival/departure time, travel/ parking period, number/type of trip; and the user adopted practices like charging/discharging moment and their location, charging/discharging power level describes the quantity, location, and timings of back and forth movement of the grid energy. Earlier studies have examined these concerns reasonably at the power system level. In this section, the results of the possible impacts originated by the EVs are replicated, pertaining mainly grid loading and electricity market pricing variations.

### A. Impact of Charging Power Level and Charging Schemes

In work in [8] the charging load profiles of EVs have been developed taking two domestic charging power levels of 3.3 kW and 6.6 kW. The combinations of these power levels and the two feasible charging schemes - constant power (CP) and constant time (CT) were performed to examine the variations in the charging load over a day. The EV load was then added to the hourly conventional load, taking a representative modified IEEE 30-Bus test system, to assess the system adequacy and fluctuations in hourly market price. The EV characteristics and mobility pattern were obtained from published research project reports of Grid for Vehicles (G4V) under European Union Seventh Framework Program [9] considering a fleet of 170000 vehicles. Home arrival timings are deduced from [10]

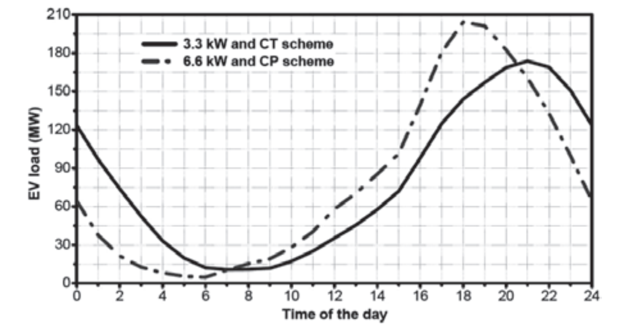


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FIG. 2 EV LOAD PROFILES WITH THE TWO CHARGING SCHEMES AND POWER LEVELS

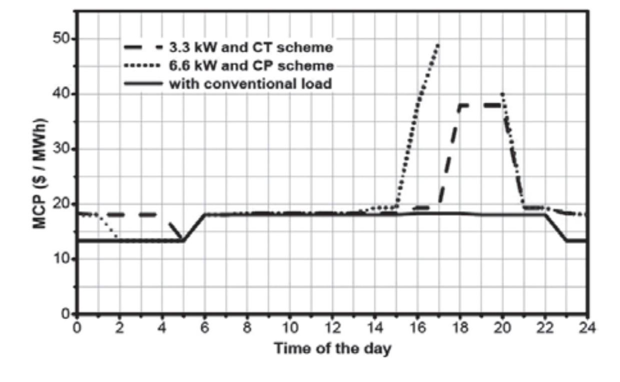


FIG. 3. HOURLY MCP WITH THE TWO CHARGING SCHEMES AND POWER LEVELS

which has considered the National Household Travel Survey (NHTS) [11] data. The selected charging power levels are as per the SAE J1772 [12] and

EPRI [13] electric vehicle charging standards. The average battery capacity is considered to be 24 kWh per vehicle and the driven distances by the vehicles were divided into 120 different mileage groups.

Figures 2 and 3 shows the load profile and the hourly market price with the two charge power levels (3.3 kW and 6.6 kW) and charging schemes of CT and CP respectively. The analysis confirms the superiority of lower charge power level coupled with the constant time charging approach since it results in lesser peak EV load in addition to shifting of it toward the late hours. This facilitates the notion of night valley filling as can be seen in Fig. 4 that the use of CT scheme with 3.3 kW charge power results in flattest charging profile among the sim- ulated scenarios. However, lower charging power means longer charging time. The owners with sufficient home parking span as well as the vehicles with higher leftover SOC (less charging energy) can go for the low charge power strategy, preventing the EV load peak being coinciding with conventional peak (Fig. 4).

**B. Impact of G2V and V2G Profiles Fusion**

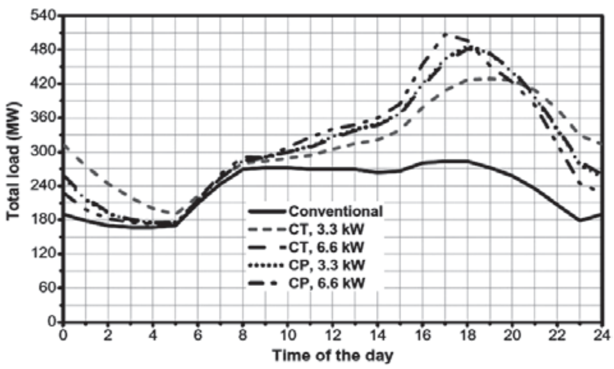


FIG. 4. TOTAL LOAD ON THE MODIFIED IEEE 30-BUS SYSTEM

As mentioned earlier, a large pool of coordinated EVs can turn out to be a quick response energy and capacity resource via flexible G2V and V2G modes of operation. The energy feedback to the grid in V2G mode has been analyzed in [14]. The work utilized the concept of workplace-discharging (V2G) and home-charging (G2V) considering equilibrium of different battery capacities as a prototype of small, medium and large vehicles present in the system. First, the G2V energy required by the EVs for driving has been evaluated by modelling the speed dependent energy consumption taking into account four different courses of driving namely, road, urban, highway and traffic. After, the SOCs of the battery is evaluated with different driven distances which in turn yields the energy available for V2G power feed. The charging (G2V) load profiles have been obtained using 1.92 kW, 2.5 kW, 3.3 kW and 6.6 kW as the charge power levels, in which vehicles start charging as soon as they arrive at home after finishing the work-related trip of the day. While the discharging (V2G) profiles are being developed for the six discharge power levels ranging from 1.44 to 6.6 kW considering their arrival at the workplace as the start time of discharge. The same fleet of 170000 vehicles has been considered. The average battery capacity comes out to be 18.54 kWh per vehicle and vehicles were able to inject 28.15% of it into the grid in V2G mode after accounting for driving consumption and 20 km range buffer. The developed V2G and G2V profiles are shown in Figs. 5 and 6 respectively. From Fig. 5 it can be observed that the rise in discharge power level increases the V2G peak together with shifting it toward the left. This is because of the increased discharging rate. The similar pattern can be observed in G2V profiles of Fig. 6 as the peak rises and shifts toward left with the increase in charge power level from 1.92 to 6.6 kW. The crest resulting in morning hours of V2G profiles (Fig. 5) and evening hours of G2V profiles (Fig. 6) characterize the driving pattern of customers for work related trips, with the majority arriving at the workplace in the morning and back at home in the evening. The net load on modified IEEE 30-Bus test system with the simultaneous fusion of V2G/G2V profiles into the conventional load is shown in Fig. 7. It can be seen that the proposed V2G and G2V mode of operation would reduce the net load on the system in the morning hours with V2G provision but at the same time, escalating it the evening and late evening hours due to G2V.

## C. Impact of EV Equilibrium under Varying Penetrations

The fusion of V2G/G2V profiles into existing system load alters the energy demand and would necessitate the adjustment in generation unit commitment. This tweak in the generator scheduling will vary the electricity market price. The effect on hourly market price under varying equilibrium of different capacities BEVs and PHEVs has been examined in [15] on the same modified IEEE 30-Bus test system. The balance of BEVs and PHEVs in the system has been varied considering three EV penetration scenarios of 25%, 50% and 100%. As the varying equilibrium modifies the aggregated battery capacity, the charging (G2V) and discharging (V2G) energy capacities are revised thereby altering the net load and hourly market price of the system on the inclusion of the resulting G2V and V2G energy profiles. The V2G and G2V power curves at the two terminal powers of 1.44 kW and 6.6 kW for the three penetration levels are shown in Figs. 8 and 9 respectively. It was observed that the average battery capacity per vehicle was largest in 50% penetration (19.77 kWh), followed by 100% (18.54 kWh) and 25% (17.68 kWh) penetrations. So, the aggregate V2G power followed the same order accounting for 29.93%, 26.17% and 24.27% of battery capacities respectively in the above three penetrations, after the driving consumption evaluation. This causes the aggregate G2V/V2G capacities not being in the direct ratio at these penetration levels. From the curves, it can be inferred that the G2V load and V2G support not only depends upon the number of vehicles connected to the grid but also on their equilibrium in the system as high

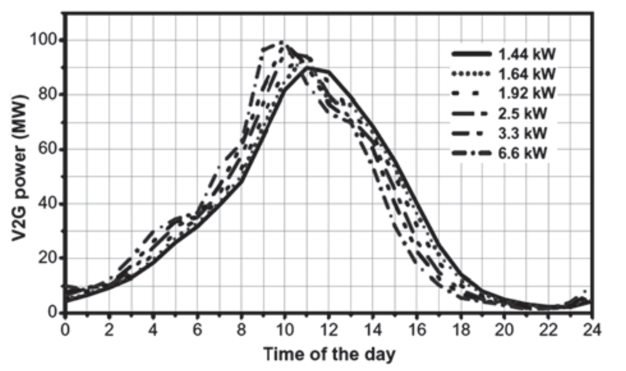


FIG. 5. V2G ENERGY PROFILES

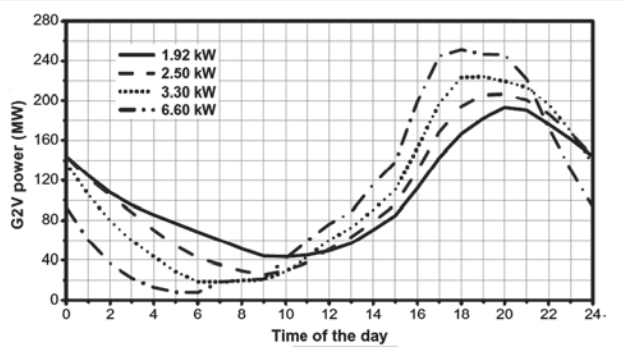


FIG. 6. G2V LOAD PROFILES

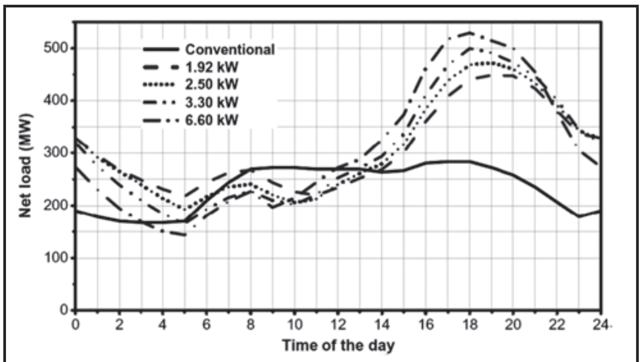


FIG. 7. NET LOAD ON MODIFIED IEEE 30-BUS SYSTEM AFTER V2G/G2V FUSION

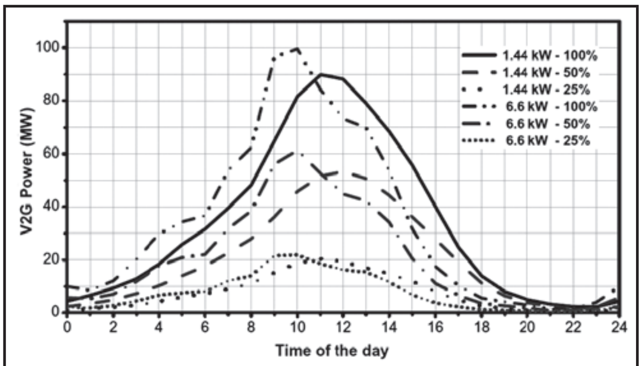


FIG. 8. V2G POWER PROFILES AT DIFFERENT PENETRATIONS

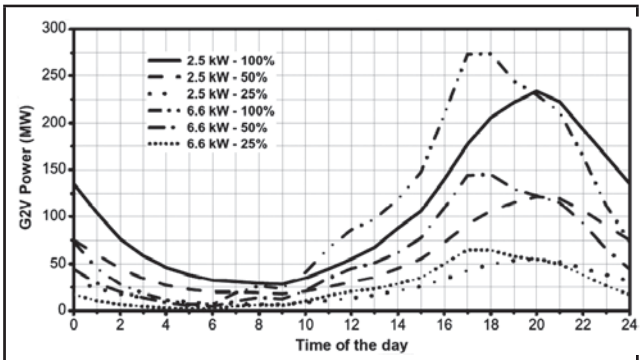


FIG. 9. G2V LOAD PROFILES AT DIFFERENT PENETRATIONS

**TABLE 1**

**CHANGE IN MARKET CLEARING PRICE (MCP) WITH G2V/V2G MODES**

| G2V/V2G mode power level (kW) | Maximum change in MCP in morning | Maximum change in MCP in evening |
|---|---|---|
| | ($/MWh) | ($/MWh) |
| 2.5 | -3.159 | +12.583 |
| 3.3 | -3.341 | +12.583 |
| 6.6 | -3.341 | +23.418 |

Note: -ve sign indicates the reduction in MCP due to V2G support, while the +ve sign implies the increase in MCP due to G2V load

capacity BEVs may contribute more to G2V/V2G than small capacity PHEVs. Simple extrapolation of figures from one penetration ratio to another neglecting vehicles heterogeneity in the system may lead to the aberration. The net load on the system and hence the hourly market price reduces in the morning with the EVs participation in V2G during the workplace parking duration. However, the reduction in the two is compensated by the hike in the evening due to G2V load put up by the home parked vehicles. The maximum change in the test system's hourly market clearing price (MCP) due to G2V/V2G operations during the workplace and home parking periods are summarized in Table I. Here, the increase in MCP (+ve value) has dominance over the decrease in MCP (-ve value) because the G2V load put up on the grid is the sum of energy consumed in the driving and that exhausted during V2G operation.

Although the technology development to make grid inte-gration of EVs a practicality is still premature, theoretically, the grid level impacts of EVs charging/discharging are well investigated. Energy market price based strategic charging for flattening the load curve [4], [16]–[18], tariff based incen-tives to shift charging time toward the off-peak periods [10], [19], charging/discharging rate control in bidirectional power transfer [20] and effect of strategic charging on generation unit commitment, power dispatch and CO2 emissions [21] are the few ones to limit the loading impact of EVs on the grid. The V2G system is also explored to mitigate the grid connected renewable energy sources' intermittency [4], [5]. At the distribution side, the voltage, congestion, transformer overloading, phase imbalances, power quality, losses, etc. [7], [22]–[24], and demand response [25] have also been investigated with a purpose to enhance integration percentage of EVs. Reference [26] provides an extensive survey of the impacts of EV charging and V2G systems at the distribution level.

## 4.0 MOBILITY ATTRIBUTES IN EV RESOURCE MODELLING

The accurate modelling of G2V and V2G power transfer profiles constrains the integration of relevant mobility features seeing the diverse behavior of the transportation system. Few of these are:

1) Types of EVs and their Equilibrium/ Composition: The knowledge of the nature of EVs - battery electric or plug-in hybrid, their sizes (battery capacity) - small, medium or large, and composition percentages in the system under consideration is the primary requirement in modelling the EV resource to assess the system-wide impacts. Their extent can vary with increased penetrations into the system.

2) Number of Trips, their Types, and Driven Mileages: The number of trips and the driven distance in each of the trip determines the energy consumption hence the state-of- charge (SOC) of the battery. The consumption further revolves around the nature of trips, i.e. whether and how much of it is carried out on highway condition or city travel condition. This is known as speed and acceleration/deacceleration dependent energy consumption which has been modelled in the works [14], [15].

3) Arrival/Departure Pattern and Travel/Parking Duration: It can be easily predicted that the EV owners would charge their vehicles while they are being parked. Depending upon the usage the possible charging spots may be the work- place, home, shopping centers, leisure centers, etc. Thus, to ascertain charging/discharging moment and its location the arrival pattern along with travel and

parking duration needs to be identified. A typical arrival pattern associated with home-workplace commute meant for work-related trips during weekdays is shown in Fig. 10. The curves have been developed from [10], [11] after discretization and simplification of home arrival times and employing workplace parking duration (7 h) and average commuting time (1.3 h) as analyzed from [27].

4) Battery Characteristics and Charging/ Discharging Pro- cess: Among present day battery technologies, Li-ion batteries (LIB) are invariably used in EVs. The charging characteristics of LIB are non-linear. The time taken for charging a LIB from about □70% to 100% capacity is almost twice the time required in initial 0 to 70% charge. This is due to the shift from constant current (CC) to constant voltage (CV) phase at around □70% capacity during charging. Ref. [10] suggested

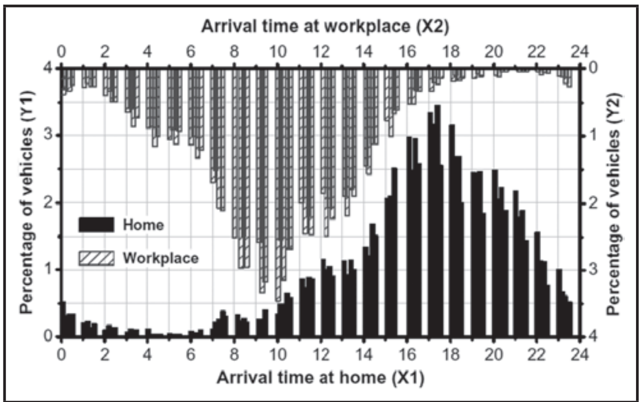

FIG. 10. ARRIVAL TIME OF VEHICLES AT HOME (X1,Y1) AND WORKPLACE (X2,Y2) TABLE II

| TABLE 2 | | | |
|---|---|---|---|
| **ELECTRIC VEHICLE CHARGING STANDARDS** | | | |
| **SAE J1772 Standard** | | | |
| **Charging type** | **Voltage level** | **Power level** | **Phase** |
| Level 1 | 120 V AC | 1.2-2.0 kW | Single-phase |
| Level 2 (low) | 208-240 V AC | 2.8-3.8 kW | Single-phase |
| Level 2 (high) | 208-240 V AC | 6.0-19.2 kW | Single-phase |
| Level 3 | 208-240 V AC | 15-96 kW | 3-phase |
| DC Level 1, 2 and 3 | 200-600 V DC | 15-240 kW | DC |
| **EPRI Charging Characteristics** | | | |
| **Charging type** | **Electrical ratings** | | |
| AC Level 1 | 120 V AC, 12-16 A, 1.44-1.92 kW, Single-phase | | |
| AC Level 2 | 208-240 V AC, 12-80 A, 2.5-19.2 kW, Single-phase | | |
| DC Level 1, 2 and 3 | 200-600 V DC, ≤80 - 400 A, ≤19.2 - ≤240 kW | | |

the charging schemes of constant power (variable time) and constant time (variable power) which has been replicated in work in [15] to suit the LIB characteristics accordingly. Further, the high charge currents, as well as deep charge-discharge cycle reduces the battery capacity and its lifetime in terms of the number of charge-recharge cycles at a particular depth-of-discharge (DoD).

5) Charging and Discharging Power Levels: For a given amount of energy required/delivered, the selection of charge/discharge power levels plays the central role in the evolution of G2V (charge)/ V2G (discharge) profiles. It directly relates to the shape of G2V load and V2G power curves. The SAE J1772 [12] and EPRI [13] EV charging standards are summarized in Table II .

## 5.0 DISCUSSION AND CONCLUSION

Transportation electrification and its grid integration will oblige utilities to develop new business 200-600 V DC, ≤80 - 400 A, ≤19.2 - ≤240 kW energy and capacity segment of the system demanding the infrastructure upgrades at different levels, their smart operation provides an opportunity to the utilities to exploit their potential for grid services (V2G) by providing the encouraging market environment. The healthy competition in bidding, scheduling, and settlement of transactions to effec- tively manage EV resource (load/generation) can enhance grid reliability with minimal investments and at the same time ben- efiting society as whole through carbon credits and reduced oil demand. This involves utilizing EV aggregation for ancillary services provision like regulation services capacity commit- ment, relieving wind power intermittency, storage of surplus renewable energy averting its spillage, etc. Thus, creation of smart charging/facility business structure is the key objective here. Assessment of grid level impacts at different levels of penetrations considering vehicles' heterogeneity is critical for the economic feasibility of smart interaction framework. Mod- elling of real mobility behavior and selection of its dependent electrical parameters adds to the procedure. Justifying the economic benefits through grid services will encourage their participation in V2G beyond the barriers of expensive battery and charging station installations. The charging/discharging will vary the dynamics of the grid requiring utilities to modify the manner in which they control the demand, supply, and load. Understanding usage patterns, recognizing charging locations and charging times will be imperative for the utilities to manage extensive EV penetration. Thus, the challenge lies in, whether the electricity sector can create a robust market for the provision of charging/discharging infrastructure and services, ensuring fair electricity rates at the same time. Equalizing the different priorities in social interests to promote rapid adoption of EVs is a way forward for the sustainable environment and clean climate.

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