Mathematical Modeling for Economic Evaluation of Electric Vehicle to Smart Grid Interaction

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***Abstract*—The objective of this work is to develop a mathematical model for the integration of electric vehicle (EVs) to the grid. Integrating the EV with the grid would help in simultaneous charging of numerous EVs and provide peak hour energy to the grid (from EV). This bi-directional exchange of energy between the grid and EV results in a complex financial calculations. So a simple model has been proposed. The energy provided by the EV to the grid depends on the battery capacity. Battery capacity is affected by capacity losses (CL). The model includes the possible cases of CL, such as CL due to battery usage (discharge during vehicle transportation) and CL due to the grid interaction. The main cause for a higher per kilometer (Km) transportation cost in EV, when compared to conventional vehicle, is the high cost of the battery and its maintenance. In this model, the economic analysis has been done in such a way that the battery related liabilities do not become a financial burden to EV owners. The above scenario has been evaluated for different combinations of charge rate (C_r) and discharge rate (D_r) ranging from $1C_r - 1D_r$ to $3C_r - 3D_r$. Finally the optimal cost of electricity is determined such that the grid, EV owners, and consumers (EV users) are benefitted.**

***Index Terms*—Battery, capacity losses, charge rate, discharge rate, electric vehicle, grid to vehicle, state of charge, vehicle to grid.**

I. Introduction

CONVENTIONAL internal combustion engine (ICE) vehicle depends on natural oil based non renewable energy sources. Along with it, the environmental issue and the regular hike in the fuel price has prompted to look for alternatives. Electric Vehicles (EVs) have emerged as an alternative to the ICE vehicles [1]. Presently researchers are trying to integrate the EVs with the recently developed technologies.

The EV's higher fuel efficiency, lower per km cost, eco-friendly are some of its advantages. EV's disadvantages are mainly in the form of limited driving range, higher refueling time (battery recharge time), higher purchasing cost (due to high cost of the battery), bulky battery size and weight [2]. The EV's named disadvantages are mainly related to the battery. Numerous research work is being carried out to neutralize all such battery related problems. Due to its other advantages, the problems associated with an EV is usually ignored. Though there is increasing demand for EVs, but its large scale implementation remains a challenge. EV's untimely charging pattern will create a major problem to the grid operators [3], [4].

Manuscript received January 16, 2013; revised June 08, 2013; accepted July 20, 2013. Date of publication September 17, 2013; date of current version February 14, 2014. Paper no. TSG-00035-2013.

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Digital Object Identifier 10.1109/TSG.2013.2275979

Simultaneous charging of a large number of vehicles can lead to grid instability. This can be avoided, if the EVs are integrated with the grid. For grid, this will provide an option to minimize peak power demand [5]–[7]. Researchers are evaluating the technical feasibility of the scheme and finding the solutions to the problems [8]. In a different approach, optimal scheduling for charging and discharging of EVs in vehicle to grid (V2G) scenario has been developed [9]. In V2G scheme, the peak hour energy supplied by the EV to the grid depends on the battery capacity. The battery capacity represents the maximum amount of energy that can be extracted from the battery. The battery capacity is affected by capacity loss (CL). CL is directly proportional to charge rate (C_r) and discharge rate (D_r) [10], [11]. The capacity of the battery also decreases with its usage and with time (due to its self-reacting chemicals). The high cost of the battery and the CL are some of the main obstacles in the large scale implementation of the EVs in the public domain.

Though the above paragraph has established the technical advantages of V2G, but to practically implement the scheme it has to be checked on the scale of its financial feasibility. The economic aspects of V2G have been reported in various literatures [12], [13]. Coordinating V2G services for energy trading has been discussed in [13].

Integrating the EV with the grid is a valuable option, if they are controlled properly [4], [14]–[19]. For the EVs, simultaneous charging of a large number of vehicles becomes viable. Without it, the grid may face voltage sag, line overloads, feeder congestions, etc. For the grid operators, it provides an option to obtain energy during peak hour. This bi-directional energy exchange depends on the C_r and D_r.

Integrating the EV to the grid results in CL of the battery, which mainly depends on C_r. This CL results in energy loss. Battery capability is mainly affected due to the CL during V2G interaction [10], [20], [21]. This loss is dependent on the chemical structure of the battery. Hence this is a characteristic loss which can never be eliminated. The CL results in financial loss to the EV owners. Also while replacing the battery, its high cost becomes a burden to the EV owners. For the EV's to sustain, EV owners should never lose money. The vehicle owners will cooperate with the grid operators only if they are financially benefited. The grid operators also have some constraints on the amount of money it can charge from consumers and the amount with which it purchases energy from the EV owners [22]. In this work, a method has been described for the grid to minimize peak hour energy demand by considering the EV as an distributed source. Further the energy transfer between the grid and the EV has been discussed at different C_r, D_r and some of the important financial results have been analyzed.

The main features of the paper has been summarized below:

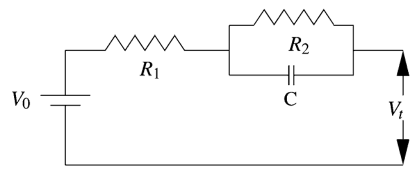

Fig. 1. Electrical equivalent circuit representation of EV battery.

- For the bi-directional flow of energy between the EV and grid, the monetary calculation for per km transportation becomes complex. This paper has made this complex calculation into a fairly simple calculation using a set of equations.
- As integration of the EVs to the grid is arguably profitable, this paper compares the per km transportation cost for the EV with and without integration to the grid. It has found that due to peak hour transfer of energy between the EVs and the grid, the per km cost for the EV integrated to the grid is higher. This is due to the losses associated with the battery during peak hour energy supply.
- In this paper, capacity loss has been determined for the integration of the EV's to the grid. Based on the capacity loss, all the major financial calculation has been done, i.e., the economics related to the capacity loss has been analyzed.
- The capacity losses in the integration of the EVs to the grid for different charge/discharge rate have been calculated.

This work is the extension of the peak load shift using the V2G. While there are many publications on the peak load shift using the V2G, the effect of capacity loss is not included in these papers. In this paper a detailed battery model has been used. Its advantages are explained below:

- Determining the Sate-of-Charge (SOC) of the battery becomes fairly easy.
- It is computationally inexpensive and avoid extensive experimentation to determine the battery parameters.
- It becomes fairly easy to calculate life, efficiency, and the capacity of the battery.
- It can easily predict the I-V characteristics. Hence it is used to study the dynamic models of the electric vehicles.[23]

The paper is organized as follows: Section II presents the capacity loss model of Li-Ion battery. The mathematical model for economic evaluation of the V2G has been formulated in Section III. In this section the process of bi-directional energy transfer between the EVs and the grid has been identified and analyzed. In Section IV, a scenario has been analyzed where the EV is not integrated to the grid. The cost benefit related calculations for energy transferred from grid to vehicle (G2V) and vehicle to grid (V2G) are discussed in Section V. In this section the energy flow from V2G and G2V is analyzed at different C_r and D_r. Section VI concludes the paper.

II. Capacity Loss Model

In this section, mathematical model for capacity loss of the EV battery is presented. The Electric Equivalent Circuit (EEC) for EV battery is shown in Fig. 1. The EEC model has three parameters: an open circuit voltage (V_0), internal resistances (R_1 and R_2) and capacitance (C). This model is used to determine the circuit parameters for different C_r and D_r. The battery parameter values are different for the different charge or discharge rate. The battery parameters are determined using the measured value of the battery manufacturer's characteristics data. If the charge or discharge rate is constant, the electrical equivalent circuit parameters (R_1, R_2, C and V_0) are approximately constant during 20% SOC to 100% SOC, but changes exponentially during 0% SOC to 20% SOC. This is due to the electrochemical reaction inside the battery [24]. The variation of small parameters among the curves for different charge or discharge rate indicate that these parameters are approximately independent of charge or discharge currents. The mathematical representations for R_1, R_2, C and V_0 under constant current charging conditions are given in [25].

The terminal voltage (V_t) of charging/discharging scenario is given below. The terminal voltage of the battery equivalent circuit depends on the parameters of the polynomial equation.

$$V_t = \left(\frac{Q}{C} + IR_2\right) \exp\left(\frac{-t}{R_2 C}\right) + V_0 - I(R_1 + R_2) \quad (1)$$

where Q is nominal capacity of the battery (Ah), I is the battery charging/discharging current (A) and t is charging/discharging time.

The quantity of energy required (E_{req}) to charge the EV battery depends on the State-of-Charge (SOC) of the battery. Mathematically,

$$E_{req} = V_t Q(SOC_{\max} - SOC_{cr}) \quad (2)$$

where SOC_{cr} is the current SOC of EV battery and SOC_{max} is the maximum SOC limit to charge the EV battery. The total processed energy (E_p^c) for charging scenario is given in (3).

$$E_p^c = \sum E_{req} \quad (3)$$

The energy available (E_{avail}) from the EV battery can be calculated using the following equation.

$$E_{avail} = V_t Q(SOC_{cr} - SOC_{\min}) \quad (4)$$

where SOC_{min} is the minimum SOC limit to discharge the EV battery. The processed energy for discharging scenario is given in (5).

$$E_p^d = \sum E_{avail} \quad (5)$$

Using (3) and (5), the total processed energy (E_p) of the EV battery can be mathematically represented as,

$$E_p = \sum_{i=1}^{n} \left(E_p^c + E_p^d\right) \quad (6)$$

It should be noted here that the total processed energy is not equal to the energy that can be processed. The total processed energy is the sum of the energy that has been injected and extracted from the battery. For example let us assume there is a 20 kWh battery. If 5 kWh is extracted from it and 5 kWh is injected back into it, then the total processed energy is 10 kWh. Whereas the total energy that can be processed is 40 kWh, i.e., if the battery is new and has 100% SOC then 20 kWh can be extracted from it and once its SOC is 0% then 20 kWh can be injected into it.

The amount of energy that can be extracted from the battery or stored in the battery decreases rapidly due to the CL in the EV battery. The CL mainly depends on total processed energy during charging/discharging, C_r, D_r and temperature [20]. C_r and D_r varies with respect to the grid condition [26]. Therefore, a mathematical model is required to predict the CL at different

C_r and D_r [25]. The battery capacity depends on certain specified conditions such as C_r, D_r, SOC, and temperature [21]. In this work, room temperature has been consider. The mathematical model for CL at different C_r and D_r is given in (7) [25].

$$Q_l = A\exp\left(\frac{CE_p^cQC_rSOC}{RT}\right) + B\exp\left(\frac{DE_p^dQD_rDOD}{RT}\right) \tag{7}$$

where A and B are the pre-exponential factors, C and D are the adjustable parameters, E_p^c is the processed energy during charging scenario (kWh), E_p^d is the processed energy during discharging scenario (kWh), Q_l is capacity loss (Ah), R is gas constant (J/mol K) and T is temperature (K). The next section presents a mathematical model for the integration of the EV to the grid.

III. Mathematical Model for Economic Evaluation

Due to the bi-directional energy transfer between the grid and the EV, determination of the amount that the consumers (who uses the EV for transportation) has to pay becomes complex. Normally the electricity tariff is based on peak and off-peak hours demand [27]. But, due to the bi-directional energy transfer, the present day tariff is not suitable for the immediate future. Therefore, a model should be formulated such that the large scale implementation of EVs does not result in a complex financial calculation. This section discusses such a possible model for V2G.

The next subsection describes all the necessary assumptions required for the model.

A. Assumptions

The following terms have been assumed.

- Peak hour is that period of the day when the demand for the electrical energy is maximum. On an average, the duration of peak hour is assumed to be 1/3 of the day i.e., 8 hours. So the duration of off-peak hour is 16 hours. Therefore the total energy consumed in a day can be mathematically represented as:

  $$E_{total} = E_{peak} + E_{off-peak} \tag{8}$$

  where E_{total} is the total energy consumed in kWh, E_{peak} is the total energy consumed during the peak hour in kWh and $E_{off-peak}$ is the total energy consumed during off-peak hour in kWh. Using (8), the monetary equivalent of energy consumed can be mathematically represented as:

  $$A = RE_{peak} + R'E_{off-peak} \tag{9}$$

  where A is the total money to be paid for energy consumption (Rs.), R is the tariff of energy during the peak hour ((Rs.)/kWh) and R' is the tariff of energy during the off-peak hour ((Rs.)/kWh).
- The EV owners are the proprietor of the EVs. The consumers are the people who use the EV for transportation only. In terms of EV-grid coordination, EV owners are the participants in V2G and G2V scheme. Consumers are participants only in the G2V scheme.
- When the EV owner uses the EV, the owner itself becomes its customer as it (the EV owner) pays for the cost incurred for transportation. The EV owners and the consumers are the different entity for the same EV.
- Efficiency of the EV battery has been assumed 90%. This lower efficiency is due to factors such as heat, faulty electrical components, etc. [28].
- For the numerical analysis the monetary value is defined as per as the Indian Currency (Rs.).
- For ease of calculation, all the financial and energy transactions are calculated per day basis.

B. Notations

While doing the mathematical modeling we need to define few notations and they are as follows:

- q is the total CL of the battery in Ah. Using (7), q can be mathematically represented as:

  $$q = \sum Q_l \tag{10}$$

- k is the percentage of energy loss due to capacity loss.
- k' is the percentage of energy loss due to other reasons such as faulty electrical connection, components, etc.
- n is the number of cycles that the battery has interacted with the grid.
- n' is the maximum number of cycles that the battery can charge/discharge in its life span (this value is fixed by the manufacturer).
- n'' is the daily average number of cycles of battery-grid interaction.
- E_{ib} is the total input energy in kWh, provided to the battery by the grid.
- E_{transp} is the energy in kWh, used by EV for the transportation purpose.
- E_{rem} is the energy in kWh, remained in the battery after vehicle transportation.
- E_q is the energy in kWh, lost due to the CL.
- E_l is the energy in kWh, lost due to other reasons.
- E_{pos} is the possible quantity of energy in kWh, available in the battery that can be sold to the grid.
- E_{sup} is the actual quantity of energy in kWh, supplied by the EV battery to the grid.
- E_{tran} is the actual quantity of energy in kWh, obtained by the grid from the EV. This is less than E_{sup} due to a lower battery efficiency.
- c is the total quantity of energy in kWh, supplied by the grid to the EV during the peak hours.
- c' is the total quantity of energy in kWh, supplied by the grid to the battery during the off-peak hours.
- s is the total quantity of energy in kWh, obtained by the grid during the peak hours.
- s' is the total quantity of energy in kWh, obtained by the grid during the off-peak hours.
- M is the initial cost of purchasing the EV battery (Rs.).
- M_{dep} is the depreciated monetary value of the battery after a particular number of cycles (Rs.).
- A_{loss} is the total financial losses to the EV owners during V2G interaction (Rs.).
- A_{cp} is net cost price of the energy for EV owners (Rs.).
- A_{gev} is the total amount paid by the grid operators to EV owner (Rs.) during a complete day.
- A_{evg} is the total amount paid by EV owner to grid operators (Rs.) during a complete day.
- A_{cg} is the total amount paid by the consumers to the grid operators (Rs.) during a complete day. In this model, consumers are the EV passengers.

- x is the tariff paid by EV owner to grid per kWh peak hour energy (Rs.).
- x' is the tariff paid by EV owner to grid per kWh off-peak hour energy (Rs.).
- x_1 is the tariff paid by consumers to grid operators per kWh peak hour energy (Rs.).
- x'_1 is the tariff paid by consumers to grid operators per kWh off-peak hour energy (Rs.).
- x_2 is the tariff paid by grid operators to EV owner per kWh peak hour energy (Rs.).
- x'_2 is the tariff paid by grid operators to EV owner per kWh off-peak hour energy (Rs.).
- z is the money charged by the EV owners to compensate for CL (Rs.).

The next subsection discusses about the energy required by the EV battery.

C. Energy Required by EV Battery

To supply the energy, the battery has to charge itself (store energy). For a battery with 90% efficiency (assumed), 10% of the energy supplied to it by the grid is always lost. Therefore 90% input energy to the battery should be equal to the energy required by the battery. Mathematically, this can be represented as:

$$\left(\frac{90}{100}\right) E_{ib} = E_{req}$$
$$\Rightarrow E_{ib} = \frac{E_{req}}{0.9} \tag{11}$$

where E_{ib} is the input energy to the battery provided by the grid.

The grid operators will charge the EV owners depending upon the total quantity of energy consumed by the battery. Using (9), the amount paid by EV owner to grid operators is given by the following equation:

$$A_{evg} = \mathrm{cx} + \mathrm{c'x'} \tag{12}$$

where A_{evg} is the total amount of money paid by the EV owners to the grid operators during a complete day, c is the total quantity of energy supplied by the grid to the EV battery during the peak hours, c' is the total quantity of energy supplied by the grid to the EV battery during the off-peak hours, x is the tariff paid by EV owner to grid operators per kWh peak hour energy (Rs.) and x' is the tariff paid by EV owner to grid operators per kWh off-peak hour energy (Rs.).

Using (12), the total energy supplied by the grid is equal to $c+c'$. Assuming grid transmission lines to be lossless, this energy is also the input energy to the battery. Therefore, this energy is equal to E_{ib}. Mathematically, this can be represented as:

$$c + c' = E_{ib}$$
$$\Rightarrow c + c' = \frac{E_{req}}{0.9} \tag{13}$$

Though the EV battery has been charged with E_{ib}, but the energy that can be extracted from it is less than E_{req}. Using (4), E_{avail} is the energy that can be extracted from the battery. The next subsection describes the possible quantity of energy that the EV can supply to the grid during stress.

D. Peak Hour Energy Supplied to Grid

During the V2G interaction the battery exchanges energy with the grid. This also results in CL. The total CL is calculated using the CL equation as mentioned in (10). This equation provides a easier method to calculate CL.

If the EV has sufficient energy after its transportation use, then only the EV can support the grid. For a battery with nominal capacity Q, the bottom level up to which the battery is usable for grid interactions and its daily requirements for transportation purposes is $Q/3$. The value of $Q/3$ chosen for transportation requirements is user defined. It has been chosen such that the initial energy that the EV can provide to the grid, after the losses, is at least 50% of the initial energy that the EVs had obtain to charge its battery. The EV owner invests in a battery that can store 3 times the energy due to the following reasons:

- EVs can support the grid during stress.
- To match performance of the conventional vehicles, EVs requires a large battery.
- EVs can sustain itself in sudden requirement of long distance travel. Fuel engine based vehicle has the option to instantaneously refill itself, at present the EV vehicles does not enjoy such facility.

The EV has remaining energy $(2Q/3)$, which also includes the losses. Mathematically,

$$E_{transp} = \frac{1}{3}(E_{avail}) = \frac{E_{avail}}{3}$$
$$E_{rem} = \frac{2}{3}(E_{avail}) = \frac{2E_{avail}}{3}$$
$$E_q = k(E_{rem}) = \frac{2kE_{avail}}{3}$$
$$E_l = k'(E_{rem}) = \frac{2k'E_{avail}}{3} \tag{14}$$

where E_{transp} is the energy used by EV for the transportation purpose, E_{rem} is the energy remained in the system after its usage for the transportation purpose, k is the percentage of energy loss due to CL, k' is the percentage of energy loss due to other reasons, E_l is the energy loss due to other reasons such as faulty circuits, components, etc. and E_q is the energy lost due to the CL. This CL is due to grid interaction and as well as transportation.

The battery has extra energy that can be sold back to the grid. It is equal to remained energy minus the losses. Mathematically,

$$E_{pos} = E_{rem} - E_q - E_l$$
$$\Rightarrow E_{pos} = \frac{2E_{avail}}{3}\left(1 - k - k'\right) \tag{15}$$

where E_{pos} is the possible amount of energy available in the battery that can be sold to the grid. It must be noted here that the energy sold by the EV owner to the grid operators may be different from the possible amount of energy available in the battery. It is the EV owners who decides and supplies the amount of energy to the grid. The above scenario is validated with the assumption that the grid obtains as much peak hour energy as provided to them.

The quantity of energy received by the grid depends on the discharging efficiency of the battery. For a 90% efficient battery (assumed), the energy obtained by the grid can be mathematically represented as:

$$E_{tran} = \frac{90}{100}(E_{\mathrm{sup}}) = 0.9E_{\mathrm{sup}} \tag{16}$$

where E_{tran} is the actual amount of energy that the grid obtains from the EV and E_{sup} is the amount of energy supplied by the EV battery to the grid.

The grid operators pay for the quantity of energy actually received from the EV. Using (9), the amount paid by the grid operators to EV owner is given by the following mathematical equation:

$$A_{gev} = \mathrm{sx_2} + \mathrm{s'x'_2} \tag{17}$$

where A_{gev} is the total amount of money paid by the grid operators to the EV owners during a complete day, s is the total energy obtained by the grid during the peak hours, s' is the total energy obtained by the grid during the off-peak hours, x_2 is the tariff paid by grid operators to EV owner per kWh peak hour energy (Rs.) and x_2' is the tariff paid by grid operators to EV owner per kWh off-peak hour energy (Rs.). Using (17), the total energy obtained by the grid is equal to $s + s'$. Mathematically, this can be represented as:

$$\begin{aligned} s + s' &= E_{tran} \\ \Rightarrow s + s' &= 0.9E_{\text{sup}} \end{aligned} \tag{18}$$

The next subsection deals with the economics related to the capacity loss.

E. Capacity Loss Compensation

For a battery, charging is the process of accumulation of energy and discharging is the process of dissipation of energy. The process of charging and discharging for one time completes one battery life cycle. Due to natural limitations, the usage of a battery is limited to a fixed number of cycles, after which the battery is of no use to the EV owner. Let M_{dep} be the depreciated value of the battery after n number of cycles of V2G interaction. The battery is expected to last n' number of cycles. The average per unit cost of the battery in terms of number of V2G cycle is M/n'. So after n number of V2G interactions, the depreciated value is given by the following mathematical equation:

$$M_{dep} = \frac{M}{n'}n = \frac{n}{n'}M \tag{19}$$

where M is the initial cost of the battery and M_{dep} is the depreciated value of the battery after n number of cycles.

The battery is associated with CL. The energy loss (E_q) due to CL is estimated by running the iteration of CL n times and assuming that only E_p amount of energy is being exchanged from the battery. This is an additional loss to the EV owners. Therefore, they should be compensated for this loss. The sum of compensation money charged by the EV owners should be greater than or equal to the monetary equivalent of the energy lost due to low capacity of the battery. This will ensure that the EV owners are beneficiary participants. Mathematically,

$$C_m \geq M_e \tag{20}$$

where C_m is the compensation money for energy loss and M_e is the money equivalent of the capacity lost.

The CL mainly depends on the number of cycles of V2G interaction and the processed energy associated with it [20]. In this work, the SOC limit has been assumed from 20% SOC to 100% SOC for charging scenario and 100% SOC to 20% SOC for discharging scenario. If the SOC limit is interrupted, then the amount of energy processed for charging and discharging scenarios will change. As the capacity losses also depends on the processed energy for charging and discharging scenario, the capacity losses will have different value if the SOC limit is interrupted. The compensation money is calculated using the above mentioned factors. Mathematically, it can be denoted as:

$$\begin{aligned} &C_m \propto n, E_p \\ &\text{or} \\ &C_m = nE_pz \end{aligned} \tag{21}$$

where z is the compensation money charged by the EV owners for CL. With time and usage, the battery does not provide the energy it had provided in the first cycle. This generates a loss of energy as well as loss of money. Therefore this loss should be compensated. As CL is a permanent loss, it can only be compensated in terms of money. Therefore, when CL is compensated, the financial losses for the EV owner are taken care off. The maximum energy available from the battery is E_{avail}. So the cost of per unit of battery is M/E_{avail}. This per unit battery cost is true only when the total energy can be used. For transportation purpose, the maximum energy that the battery can use is up to $E_{avail}/3$. The remaining energy is $2E_{avail}/3$, which also includes the losses (capacity and other loss). The CL depends on the number of cycles of V2G interaction, so z is calculated using the depreciated value of the battery. Therefore, the per unit energy cost which also includes the losses of the battery is $M_{dep}/(2E_{avail}/3)$. So the monetary equivalent of the CL of the battery can be mathematically represented as:

$$M_e = \frac{3M_{dep}}{2E_{avail}}E_q \tag{22}$$

Using (19)–(22) the above condition is formulated below:

$$\begin{aligned} nE_pz &\geq \frac{3M_{dep}}{2E_{avail}}E_q \\ z &\geq \frac{3M_{dep}E_q}{2E_{avail}nE_p} \end{aligned} \tag{23}$$

Using (23), the value of z can be determined. It should be noted that the EV's CL is due to grid support during peak hour. Therefore EV owners' CL is compensated by the grid. Eventually the grid obtains it from the consumers while selling the energy in peak hours. The next subsection presents the amount of money that has to be paid by the grid operators (for peak hour energy) to the EV owners.

F. Determination of Tariff for the Grid Operators

The high cost of battery (M) and the CL of the battery are the major financial liabilities of the EV owners. For EV owners, these liabilities can be attributed to as losses. Mathematically,

$$A_{loss} = z + M_{dep} \tag{24}$$

where A_{loss} is the total losses to the EV owners during V2G interaction. The total cost price of energy for the EV owners is the sum of the money paid to the grid operators to charge the EV battery and the loss incurred during V2G interaction. Mathematically,

$$\begin{aligned} A_{cp} &= A_{evg} + A_{loss} = A_{evg} + z + M_{dep} \\ \Rightarrow A_{cp} &= cx + c'x' + z + \left(\frac{nM}{n'}\right) \end{aligned} \tag{25}$$

where A_{cp} is net cost price of the energy for the EV owners. In (25), z and M_{dep} are dependent on the full battery discharge. It may take days or months or years for the battery to discharge completely. Therefore, (25) has to be normalized. Mathematically,

$$A_{cp} = cx + c'x' + \frac{z + \frac{nM}{n'}}{D} \tag{26}$$

where D is the number of days the battery takes to depreciate its value to zero. D can be mathematically represented as

$$D = \frac{n'}{n''} \tag{27}$$

where n' is the maximum number of cycles that the battery can charge/discharge in its life span (this value is fixed by the manufacturer) and n'' is the average number of cycles of daily G2V interaction. From the economic point of view, this cost price has to be raised by selling energy to the grid operators. Mathematically,

$$A_{cp} = A_{gev}$$
$$\Rightarrow \mathrm{cx} + \mathrm{c'x'} + \frac{z + \frac{nM}{n'}}{D} = \mathrm{sx_2} + \mathrm{s'x'_2} \tag{28}$$

For the EV owner to get profit,

$$\mathrm{x_2} \geq \mathrm{x}$$
$$\mathrm{x'_2} \geq \mathrm{x'} \tag{29}$$

The cost of per kWh energy charged by the EV during selling is more than the money it had paid to buy the energy. The cost charge by the EV also includes the battery cost and the capacity loss. As a result EV always gains money, whenever they sell energy to the grid. The next subsection determines the amount the consumers (passengers) have to pay for EV transportation service.

G. Determination of Tariff for the Consumers

The grid had supplied energy $(E_{req}/0.9)$ to the EV. The EV pays for it and the grid operators obtain its cost price. When the EV sells back the energy $(0.9E_{\sup})$ to the grid, the EV gets its money including its battery price. So if the consumers pay for $(0.9E_{\sup})$, then the total quantity of energy exchanged during the complete process is financially accounted. Using (9), the amount paid by the consumers to grid operators is given by the following mathematical equation:

$$A_{cg} = \mathrm{sx_1} + \mathrm{s'x'_1} \tag{30}$$

where A_{cg} is the total amount of money paid by the consumers to the grid operators during a complete day, x_1 is the tariff paid by consumers to grid operators per kWh peak hour energy (Rs.) and x'_1 is the tariff paid by consumers to grid operators per kWh off-peak hour energy (Rs.).

For the grid operators to get profit,

$$\mathrm{x_1} \geq \mathrm{x_2}$$
$$\mathrm{x'_1} \geq \mathrm{x'_2} \tag{31}$$

The next section presents the scenario where EV uses its complete energy for transportation without supporting the grid.

IV. Electric Vehicle Without Supporting the Grid

This section presents the scenario where EV is not supporting the grid during peak hour stress. The EV uses its complete energy for transportation. An EV with a battery of 80% SOC, nominal capacity 100 Ah, constant terminal voltage 400 V and 90% efficiency has been considered in this section. The capacity of the battery for the complete life cycle for different C_r and D_r is shown in Fig. 2.

The critical level (or value) has been chosen based on the battery capacity. When the battery capacity is reduced to 46.65 Ah, the corresponding cycle number is called critical value. Using (11) and (12), the financial parameters are calculated and listed in Table I. It is observed that the average per km transportation cost for $1C_r - 1D_r$ to $3C_r - 3D_r$ is almost same. This is due to the fact that the per unit battery cost is almost same for all the $C_r - D_r$.

The next section presents the cost benefit related calculations for a model where EV is supporting the grid during peak hour. This section discusses the financial aspects of V2G and G2V.

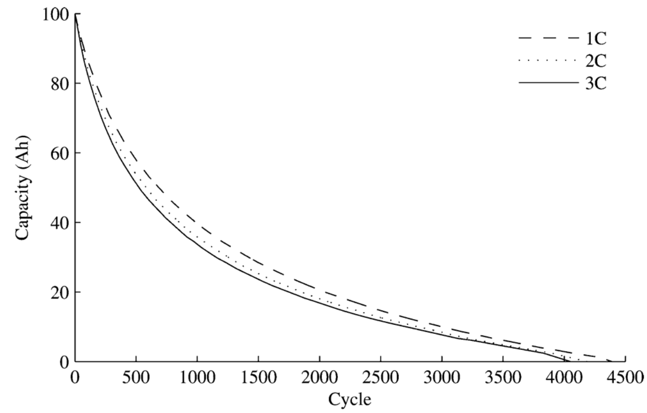

Fig. 2. Capacity loss for a 40 kWh battery without grid-interaction.

TABLE I
AVERAGE FINANCIAL VALUE FOR A NORMAL EV

	$1C_r$ - $1D_r$	$2C_r$ - $2D_r$	$3C_r$ - $3D_r$
Battery reaches its critical level	2664^{th} cycle	2461^{th} cycle	2352^{th} cycle
Consumer pay to Grid (Rs.)	254.84	264.13	269.78
Cost/Per km (Rs.)	1.13	1.17	1.20

V. Analysis of Energy Trading Scenario Under Different Charging/Discharging Rates

Among the present types of batteries, Li-ion battery has a low self-discharging rate. Also Li-ion battery has better energy density, long durability, low cost, and intrinsic safety when compared to other battery types [29]. Therefore Li-ion battery has been considered for this model. Nowadays the Li-ion battery is widely used in the EV. Generally the EV uses battery which ranges from 20 kWh to 55 kWh [30], [31]. In this work, a 40 kWh battery system has been considered.

For a 40 kWh battery system, the voltage and current associated with it must be high. With high current, the I^2R loss increases. Therefore a nominal value of current is desired to minimize this loss. For the present work, a battery with nominal capacity 100 Ah and constant terminal voltage of 400 V is considered [32].

The total CL is mathematically calculated using (10). At present, the parameters required in (10) are not available for the required battery. So, the parameters of a chosen battery are theoretically (by simulation) expanded to meet the desired condition. Here a SONY 18650 US battery has been used to produce the required data. It should be noted that the battery parameters and its associated characteristics varies with respect to the type of battery and its manufacturer.

Assuming SOC of the battery to be 80%, the maximum energy that can be extracted from the battery is 32 kWh. After complete discharge, the battery has to be charged with 32 kWh of energy. Out of this, 10.67 kWh (32 kWh/3) is used for transportation and 21.33 kWh (2/3(32 kWh)) is the remained energy

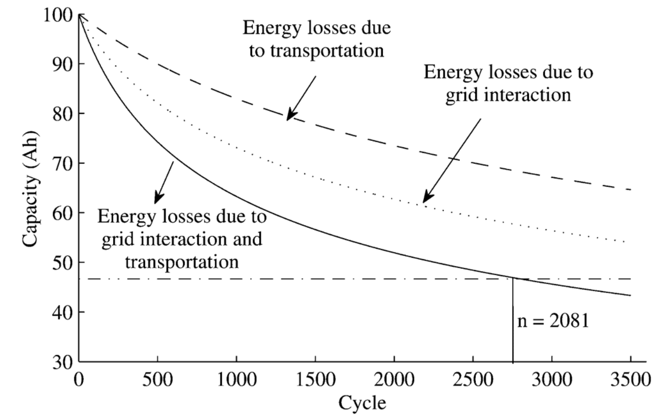

Fig. 3. Capacity loss for 53.33 kWh energy interactions of a 40 kWh battery $(1C_r/1D_r)$.

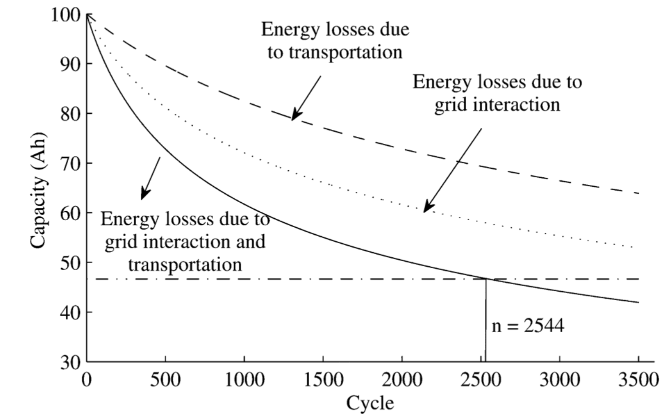

Fig. 4. Capacity loss for 53.33 kWh energy interactions of a 40 kWh battery $(2C_r/2D_r)$.

that can be used for grid support. This 21.33 kWh also includes the losses. The energy required for EV's transportation is constant, but the energy supplied by the EV to grid during peak hour decreases as capacity of the battery decreases. Mathematically,

$$\begin{aligned} E_{req} &= 32 \text{ kWh} \\ E_{tran} &= \frac{32 \text{ kWh}}{3} = 10.67 \text{ kWh} \\ E_{rem} &= \frac{2}{3}(32 \text{ kWh}) = 21.33 \text{ kWh} \end{aligned} \tag{32}$$

The CL of the battery results in its lower energy storing capability. The battery can be used till it supplies sufficient energy for EV's transportation. Therefore, the battery is useful till it can store and supply 10.66 kWh. Hence, the useful energy that the battery supplies for supporting the grid is 21.34 kWh (32 kWh–10.66 kWh). The constant terminal voltage is 400 V. Therefore, the useful nominal capacity range is 53.35 Ah (21.34 kWh/400 V). Hence, the battery is useful till its nominal capacity has reached 46.65 Ah (100 Ah–53.35 Ah). The i^{th} cycle, until which the battery is useful, is said to be the critical point of the battery. In this model, n is the critical point and it is the maximum number of cycle of possible G2V and V2G interaction.

The capacity of the battery during the complete life cycle under different C_r and D_r are shown in Fig. 3 to Fig. 5. The graphs are expectedly similarly decreasing in nature, as it represent the capacity of the battery. This decreasing in the capacity is due to the capacity loss. The graphs obtained are linear in nature. It has been claimed by some of the manufacturers that the capacity loss are linear in nature. In this paper the capacity loss are calculated using base values (data) provided by the manufacturers. In the above graph the only difference lies in the number of cycles required to reach the critical value (n). As the CL is directly proportional to the C_r and D_r, higher C_r or D_r degrades the battery very quickly. This can be seen in Fig. 3 to Fig. 5. While $3C_r - 3D_r$ takes 2041 cycles to reach its critical state, $2C_r - 2D_r$ takes 2544 cycles and $1C_r - 1D_r$ takes 2801 cycles to reach its respective critical state.

To calculate the monetary equivalent of the energy losses, the cost of the battery is required. The optimum cost of a high energy Li-ion battery is approximated to be 7500 (Rs.)/kWh, so the total cost of purchasing the 40 kWh battery, (M) comes out to be 3 00 000 (Rs.) [33].

For mathematical calculation, certain parameters are assumed and they are as follows:

- The EV charge their battery during the off-peak hours. Using (13), $c = 0$ and $c' = E_{req}/0.9$.

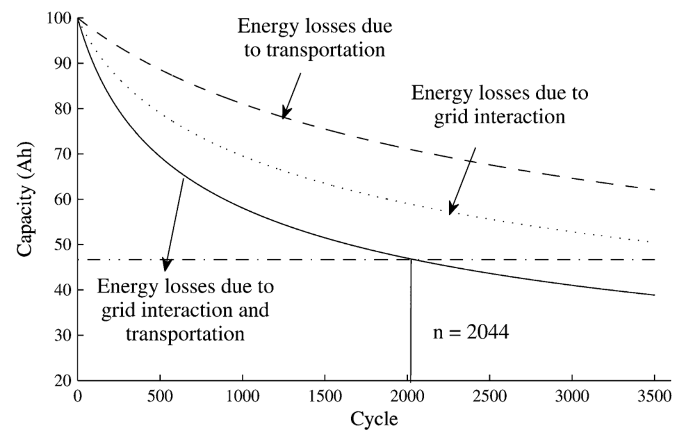

Fig. 5. Capacity loss for 53.33 kWh energy interactions of a 40 kWh battery $(3C_r/3D_r)$.

- The EV supports the grid during peak hours. Using (18), $s = 0.9E_{\text{sup}}$ and $s' = 0$
- The peak rate of energy consumption (x_i) is assumed to be 40% higher than the off-peak consumption rate (x_i'). $\mathrm{x_i} = 1.4(\mathrm{x_i'})$
- The off-peak hour electrical tariff in Assam, India is 4 (Rs.)/kWh [22]. During charging, the EVs are consumer to the Grid. Therefore, $x = 5.6$ (Rs.) and $x' = 4$ (Rs.).
- The EV will charge itself during the off-peak hours and support the grid in the peak hours. This process will take a complete day. Therefore, the average number of daily grid interactions can be assumed to be 1. Mathematically, $n'' = 1$.
- Using (27), the number of days, required by the battery to completely discharge is shown below: $D = n'/n'' = n'/1 = n'$
- An EV with 40 kWh battery is expected to give a mileage of 225 km (141 miles) per charge [34].
- Let the profit percentage be p (assumed). Using (31), x_1 can be mathematically represented as:

$$\mathrm{x_1} = \mathrm{x_2}\left(1 + \frac{p}{100}\right) \tag{33}$$

In this model p has been assumed to be 0.1% such that x_1 remains as low as possible.

Using (4), (6), (14), (19), and (25), the compensation money for CL for $1C_r - 1D_r$, $2C_r - 2D_r$ and $3C_r - 3D_r$ is shown in Fig. 6. The compensation money is highest for $3C_r - 3D_r$, when the battery discharges comparatively faster than $1C_r - 1D_r$ and

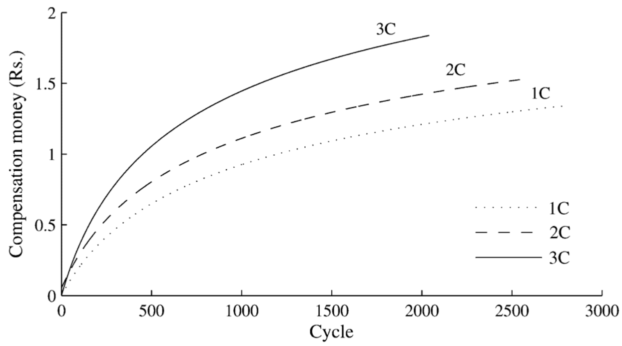

Fig. 6. Compensation money charged by the EV owners for capacity loss of the battery.

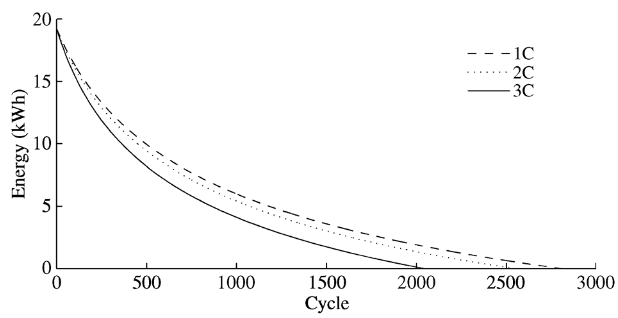

Fig. 7. Energy obtained by the grid in kWh during V2G interaction.

$2C_r - 2D_r$. This is due to the fact that per cycle battery cost is highest in $3C_r - 3D_r$. So, $3C_r - 3D_r$ is the favorable case for the EV owners. It can be observed from the graph that the z is lower than expected. With capacity loss the ratio M_{dep}/E_{avail} increases, but the ratio E_q/E_p decreases very quickly, as E_p increases with each cycle. Also n in the denominator further normalizes the compensation money. These factors contribute to the low compensation money for capacity loss. In the work, the total processed energy has been considered for calculating the compensation money for capacity losses. This can be replaced by the processed energy during discharging process, whenever required.

Using (15) and (16) the net energy obtained by the grid during V2G interaction is shown in Fig. 7. Maximum energy is transferred during the first cycle and least during the last. The per cycle average transferred energy is same for $1C_r - 1D_r$, $2C_r - 2D_r$ and $3C_r - 3D_r$. As n is more for $1C_r - 1D_r$, maximum quantity of energy is transferred in this case. Hence $1C_r - 1D_r$ is the most useful case for the grid as it gets the maximum possible energy.

Using (23), (27), and (28), the tariff paid by grid operators to EV owner per kWh energy (x_2) is shown in Fig. 8. x_2 is linearly increasing upto 1401 cycles. Therefore only the linear part of x_2 has been shown in the graph. Since the EV deals in money only with the grid operators, this is the only way to generate profit for them. The EV accommodates its financial liabilities by charging a higher tariff for the peak hour energy (from grid operators). With decreasing capacity of the battery, the energy supplied to the grid goes on decreasing and its tariff goes on increasing. This scenario is due to the fact that the cost of energy for the EV remains the same, but the quantity of its extra energy for selling becomes less. So to recover the money, the EV charges a higher tariff. The tariff is inversely proportional to the quantity of energy sold by the EV to grid. x_2 is maximum at the critical point.

Using (15)–(17), the money paid by the grid operators for grid stress energy to the EV is shown in Fig. 9.

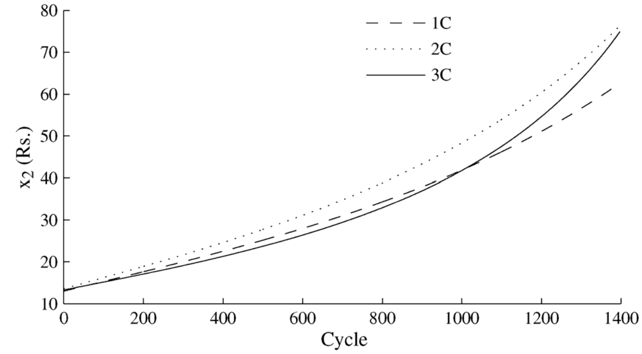

Fig. 8. Tariff paid by grid operators to EV owner per kWh energy.

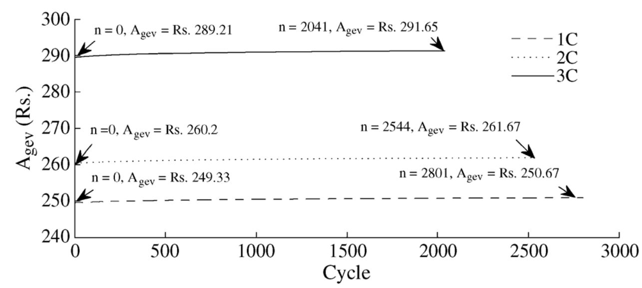

Fig. 9. Money paid by the grid operators to the EV for the grid stress energy.

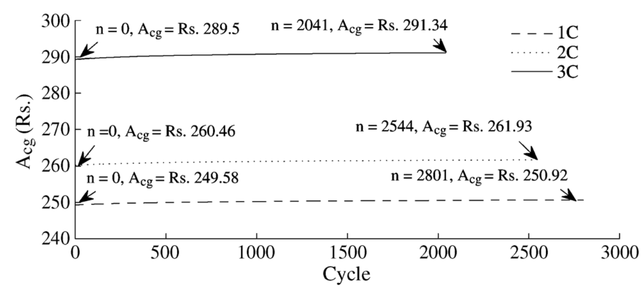

Fig. 10. Money paid by the consumers to the grid operators for the energy used by EV for transportation.

Using (18), (30), and (31), the money paid by the consumers (for transportation usage) to the grid operators is shown in Fig. 10.

As the variation in the compensation money for the CL is very low, A_{gev} and A_{cg} is almost constant for the complete battery cycles. The money paid in $1C_r - 1D_r$ in both cases is lower when compared to $2C_r - 2D_r$ and $3C_r - 3D_r$. This is due to the fact that in $1C_r - 1D_r$ the per cycle battery cost is lower when compared to $2C_r - 2D_r$ and $3C_r - 3D_r$. Hence the average cost price of energy for the EV is lower in $1C_r - 1D_r$.

The grid operators and the EV should benefit for their service. For the EV owners, cost price is the money paid for obtaining the energy to recharge the battery and revenue is the money obtained by providing grid services. Mathematically, the EV's profit and grid operators's profit can be denoted as:

$$profit = revenue - cost\ price$$
$$EV_{profit} = A_{gev} - A_{cp} \tag{34}$$

For the grid operators, cost price is the money paid for obtaining the energy from the power generation set-up and the EV owners (during grid stress) and revenue is the money they obtain from the EV owners (charging the EV) and the consumers (transportation).

$$Grid_{profit} = A_{cg} + A_{evg} - A_{gev} - A_{cpg} \tag{35}$$

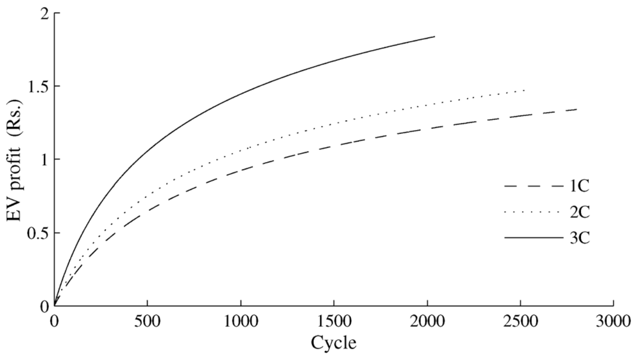

Fig. 11. Profit Obtained by EV per day for transportation and V2G interaction.

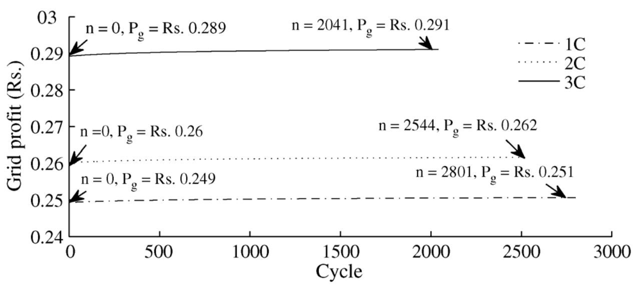

Fig. 12. Profit obtained by the grid operators per day in V2G interaction.

where A_{cpg} is the cost price of the energy which is sold by the grid operators to the EV.

Using (17), (26), (27), and (31), the profit gained by the EV is shown in Fig. 11.

Using (12), (17), and (30), the profit gained by the grid operators is shown in Fig. 12.

While EV profit increases with battery cycle, grid operators' profit is almost constant for the complete battery cycle. This is due to the fact that while the EV owners receives the compensation money for the CL, the grid operators does not receives any such financial benefits. Also the profit gained in both the cases are extremely small. The profits can be desirably increased by manipulating x_2. Here the least possible value of x_2 was considered such that the consumers had to pay the least possible amount. when compared $3C_r - 3D_r$ proves to be a better option for the EV owners and the grid operators. In this model the battery has been assumed to reach its zero depreciated value when its capacity reaches 10.66 kWh or 46.65 (Ah). In reality this battery can again be used for different purposes. So this depreciated battery is also worth money which varies locally. This turns to be added profit to the EV owners. Also the consumers pays for the energy during grid stress. So this energy is available to the grid as zero cost energy, which it sells to get an extra profit.

Using the above data (Fig. 6 to Fig. 12) the average values of the parameters are listed in Table II. It is observed that the money paid by the EV to the grid operators is same for $1C_r - 1D_r$, $2C_r - 2D_r$ and $3C_r - 3D_r$. Ideally the EV should be penalized for fast charging. Any penalty for the EV will result in a higher tariff for the grid operators, which will force the consumers to pay more. To avoid financial burden to the consumers, the EVs are not penalized. Table II also shows the cost per km for different C_r and D_r. $1C_r - 1D_r$ is the most favorable case for consumers. Also, it can be seen that the average energy required during grid stress is 5.41 kWh and the EV uses 10.66 kWh of energy for transportation. So the passengers (consumers) pays for 50.75% of the net energy used for transportation. This will prompt the consumers to willingly pay for the grid support energy.

TABLE II
AVERAGE VALUES OF THE FINANCIAL AND ENERGY TRANSACTIONS

	$1C_r$-$1D_r$	$2C_r$-$2D_r$	$3C_r$-$3D_r$
Battery reaches its critical level	2801^{th} cycle	2544^{th} cycle	2041^{th} cycle
z_{min} (Rs.)	0.97	1.06	1.32
Energy obtained by Grid(kWh)	5.41	5.41	5.41
A_{gev} (Rs.)	250.54	261.52	290.82
A_{veg} (Rs.)	142.223	142.223	142.223
A_{cg} (Rs.)	250.30	261.12	290.53
x_2 (Rs.)	46.31	48.36	53.73
EV profit (Rs.)	0.97	1.12	1.32
Grid profit (Rs.)	0.25	0.26	0.29
Cost/Per km (Rs.)	3.34	3.49	3.88

Using Table I and Table II, it can be seen that the EV supporting the grid during peak hour has a higher average per km transportation cost when compared to an EV, which is not supporting with the grid. But still integration of the EV with the grid is more useful, as stated by the following points:

- It supports the grid when required.
- The consumers pays for almost half the energy (it had used for transportation) at an escalated price. With technology development this price is expected to be lower.

With technological development, this is also going to be financially beneficiary. Also in grid supporting scheme, only one-third of the total energy is used for transportation. In the other scheme, all the energy was utilized for transportation. This is the main cause for the higher per km cost of transportation for the EV integrated with the grid. Integration of the EV with the grid is desired, as this will enable an option for grid support when required.

VI. CONCLUSION

During the peak hour, grid requires extra energy to fulfil the energy demand. The EVs would supply energy to the grid during peak hour and recharge itself during the off-peak hour. This will enable the EVs to act as a distributed energy source. A mathematical model for evaluation of the bi-directional energy transfer from vehicle to grid and grid to vehicle was formulated. The bi-directional energy transfer was discussed at different charge/discharge rate. The CL model was used to study the performance of battery during V2G interaction. The total energy exchanged between the grid and the vehicle was analyzed. On the basis of energy transfer, the money exchanged among the grid, EV, and the consumers (EV users) was determined such that all are benefitted. This paper has presented a possible financial model for integrating the vehicle to the grid. This model can be used in any given scenario of grid to electric vehicle interactions.

REFERENCES

[1] R. Argueta, "The electric vehicle" [Online]. Available: http://www.writing.ucsb.edu/faculty/holms/Writing_2E-_EV_Technical_Research_Report.pdf

[2] N. Bhat, "Advantages and disadvantages" [Online]. Available: http://library.thinkquest.org/C008050/ecars4.html

[3] G. Stoeckl, R. Witzmann, and J. Eckstein, "Analyzing the capacity of low voltage grids for electric vehicles," in *Proc. IEEE Electr. Power Energy Conf. (EPEC)*, Oct. 2011, vol. 3, no. 1, pp. 415–420.

[4] U. Reiner, C. Elsinger, and T. Leibfried, "Distributed self organising electric vehicle charge controller system: Peak power demand and grid load reduction with adaptive ev charging stations," in *Proc. IEEE Int. Elect. Veh. Conf. (IEVC)*, Mar. 2012, vol. 3, no. 1, pp. 1–6.

[5] J. Tomic and W. Kempton, "Using fleets of electric-drive vehicles for grid support," *J. Power Sources*, vol. 168, pp. 459–468, Mar. 2007.

[6] J. A. P. Lopes, "Demystifying the smart grid Boston," *Electric Vehicle Grid Integration*, Nov. 2009.

[7] S. I. Inage, "Modelling load shifting using electric vehicles in a smart grid environment" [Online]. Available: https://www.iea.org/publications/freepublications/publication/load_shif ting.pdf

[8] L. P. Fernández, T. G. S. Román, R. Cossent, C. M. Domingo, and P. Frías, "Assessment of the impact of plug-in electric vehicles on distribution networks," *IEEE Trans. Power Syst.*, vol. 26, no. 1, pp. 206–213, Feb. 2011.

[9] Y. He, B. Venkatesh, and L. Guan, "Optimal scheduling for charging and discharging of electric vehicles," *IEEE Trans. Smart Grid*, vol. 3, no. 3, pp. 1095–1105, Sep. 2012.

[10] G. Ning, B. Haran, and B. N. Popov, "Capacity fade study of lithium-ion batteries cycled at high discharge rates," *J. Power Sources*, vol. 117, no. 1–2, pp. 160–169, May 2003.

[11] P. Ramadass, B. Haran, R. White, and B. N. Popov, "Mathematical modeling of the capacity fade of Li-ion cells," *J. Power Sources*, vol. 123, no. 2, pp. 230–240, Sep. 2003.

[12] D. Wu, D. C. Aliprantis, and L. Ying, "Load scheduling and dispatch for aggregators of plug-in electric vehicles," *IEEE Trans. Smart Grid*, vol. 3, no. 1, pp. 368–376, Mar. 2012.

[13] T. Ali, A. Awami, and E. Sortomme, "Coordinating vehicle-to-grid services with energy trading," *IEEE Trans. Smart Grid*, vol. 3, no. 1, pp. 453–462, Mar. 2012.

[14] M. Singh, P. Kumar, and I. Kar, "Implementation of vehicle to grid infrastructure using fuzzy logic controller," *IEEE Trans. Smart Grid*, vol. 3, no. 1, pp. 565–577, Mar. 2012.

[15] S. Shao, M. Pipattanasomporn, and S. Rahman, "Grid integration of electric vehicles and demand response with customer choice," *IEEE Trans. Smart Grid*, vol. 3, no. 1, pp. 543–550, Mar. 2012.

[16] M. Singh, P. Kumar, and I. Kar, "Analysis of vehicle to grid concept in indian scenario," in *Proc. 14th Int. Power Elect. Motion Control Conf. (EPE/PEMC)*, Sep. 2010, no. 1, pp. 149–156.

[17] T. Morgan, "Smart grids and electric vehicles: Made for each other," [Online]. Available: http://www.internationaltransportforum.org/jtrc/DiscussionPapers/DP201202.pdf

[18] J. A. P. Lopes, F. J. Soares, and P. M. R. Almeida, "Integration of electric vehicles in the electric power system," *Proc. IEEE*, vol. 99, no. 1, pp. 168–183, Jan. 2011.

[19] S. Han and S. Han, "Economics of V2G frequency regulation in consideration of the battery wear," in *Proc. 3rd IEEE PES Int. Conf. Exhib. Innov. Smart Grid Technol. (ISGT)*, Oct. 2012, pp. 1–8.

[20] P. Ramadass, B. Haran, R. White, and B. N. Popov, "Capacity fade of Sony 18650 cells at elevated temperature: Part I. cycling performance," *J. Power Sources*, vol. 112, no. 2, pp. 606–613, Nov. 2002.

[21] A. T. Stamps, C. E. Holland, R. E. White, and E. P. Gatzke, "Analysis of capacity fade in a lithium ion battery," *J. Power Sources*, vol. 150, pp. 229–239, Oct. 2005.

[22] Assam Electricity Regulatory Commission (AERC) [Online]. Available: http://aerc.nic.in/

[23] P. Kumar and P. B. G, "Parameter extraction of battery models using multiobjective optimization genetic algorithms," in *Proc. 14th Int. Power Elect. Motion Control Conf. (EPE/PEMC)*, Sep. 2010, pp. T9-106–T9-110.

[24] M. Chen and G. Rincon-Mora, "Accurate electrical battery model capable of predicting runtime and I-V performance," *IEEE Trans. Energy Convers.*, vol. 21, no. 2, pp. 504–511, Jun. 2006.

[25] K. Thirugnanam, H. Saini, and P. Kumar, "Mathematical modeling of li-ion battery for charge/discharge rate and capacity fading characteristics using genetic algorithm approach," in *Proc. Transp. Electrification Conf. Expo. (ITEC)*, Jun. 2012, pp. 1–6.

[26] D. Trowler and B. Whitaker, "Bi-directional inverter and energy storage system," *Texas Instruments Analog Design Contest*, May 2008.

[27] Indian Express, "Different power rates for peak, off-peak hours" [Online]. Available: http://www.indianexpress.com/news/soon-different-power-rates-for-peak-offpeak-hours/917100

[28] nlukin, "Battery charging and discharging losses" [Online]. Available: http://www.teslamotors.com/forum/forums/battery-charging-and-discharging-losses

[29] W. Luo, C. Lv, L. Wang, and C. Liu, "Study on impedance model of li-ion battery," in *Proc. 6th IEEE Conf. Ind. Elect. Appl. (ICIEA)*, Jun. 2011, pp. 1943–1947.

[30] "Electric vehicles: Compare side-by-side," U.S. Dept. Energy [Online]. Available: http://www.fueleconomy.gov/feg/evsbs.shtml

[31] "Electric vehicle" Battery University [Online]. Available: http://www.batteryuniversity.com/learn/article/electric_vehicle

[32] B. Berman, "The hybrid car battery: A definitive guide" [Online]. Available: http://www.hybridcars.com/hybrid-car-battery

[33] "Costs of lithium-ion batteries for vehicles," Center for Transportation Research Argonne National Laboratory [Online]. Available: http://www.transportation.anl.gov/pdfs/TA/149.pdf/

[34] "EV glossary," Simanaitis [Online]. Available: http://simanaitissays.com/2012/12/04/ev-glossary/

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