INTELLIGENT CHARGING SCHEDULING OF PEVs & PRIORITY PREMIUM DETERMINATION FOR USERS' IN PARKING STATION

A Project Report

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THESIS CERTIFICATE

This is to certify that the thesis titled **INTELLIGENT CHARGING SCHEDULING OF PEVs & PRIORITY PREMIUM DETERMINATION FOR USERS' IN PARKING STATION**, submitted by **Vinit Khemka**, to the INDIAN INSTITUTE OF TECHNOLOGY, MADRAS, for the award of the degree of **Master Of Technology**, is a bona fide record of the research work done by him under our supervision. The contents of this thesis, in full or in parts, have not been submitted to any other Institute or University for the award of any degree or diploma.

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ABSTRACT

KEYWORDS: Grid-to-Vehicle (G2V), Intelligent charging, Plug-In Electric Vehicle (PEV), Priority Charging, Priority Premium, Vehicle-to-Grid (V2G)

The electrification of transport is seen as one of the main pathways to achieve significant reductions of Carbon Footprints. However, there are some issues related to it like, a sudden increase in electricity demand, high charging cost in dynamic price market, attending user's priority in charging his/her vehicle and the premium to be levied for such priority. In this project, an intelligent charging strategy for Plug-in Electric Vehicle(PEV) incorporating a unified grid-to-vehicle(G2V) and vehicle-to-grid(V2G) framework with users' priority is proposed for optimal integration of PEVs in the existing distribution system. An intelligent strategy with objective function considering minimization of total charging cost, with users' priority as well as without priority is developed to study the impact of PEV integration from economic and technical perspective. The proposed strategy is implemented on test bench case consisting of 5 PEVs in a parking station. The uncertain parameters like PEV availability at charging station are handled using Monte-Carlo simulation. The bi-linear constraints are modified to pose the problem as a linear optimization problem. A comparative analysis is done on the charging cost with priority and without priority to investigate the economic impact of introducing users' priority. Finally, an investigative study is conducted to assign economic value to priority so that the premium can be charged from users for assigning priority to their vehicles. The simulation results present a comprehensive evaluation of the proposed strategy.It was observed that introducing priority causes more charging cost and hence a loss of opportunity cost is involved, which is levied as premium to users.

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ABBREVIATIONS

V2G	Vehicle To Grid
G2V	Grid To Vehicle
BE	Battery Energy
PEV	Plug-In Electric Vehicle
EV	Electric Vehicle
SoC	State Of Charge
GAMS	General Algebraic Modeling System
NLP	Non-Linear Programming
MILP	Mixed Integer Linear Programming
LP	Linear Programming

NOTATION

$\mathbf{U}_{V\_Gij}$	Energy transferred from j^{th} vehicle to grid in i^{th} time slot,kWh
$\mathbf{U}_{G\_Vij}$	Energy transferred from grid to j^{th} vehicle in i^{th} time slot,kWh
T	Number of Time Slots in a day
N	No of cars available for charging in Parking
η_j	Efficiency of jth PEV battery and converter(same for charging and discharging)
π_j	Price of one unit electricity in ith time slot,Rs/kWh
$\mathbf{P}_{ij}$	1 if in ith time slot jth EV is present in parking for charging , 0 otherwise
$\mathbf{BatConst}_j$	Battery constant for jth EV's Battery
$\mathbf{P}_{max}$	Maximum power rating of each charging station,kW
μ_{ij}	System's Priority of jth EV at starting of timeslot i
$\mathbf{d}_{ij}$	Duration for which jth EV will remain in parking station at the start of timeslot i,Hr
maxload	Maximum load which can be connected to grid from parking station,kWh
$\mathbf{W}_j$	Weight given by user for charging his/her vehicle at high priority
M	A very large number say 10000 for NLP to MILP conversion using Big-M method
$\mathbf{b}_{ij}$	Binary variable which decides whether V-G or G-V operation takes place
$\mathbf{BE}_{ij}$	Energy contained in the jth EV's Battery at end of timeslot i,kWh
$\mathbf{BE}_{ijopt}$	Optimal battery energy should be stored in battery
$\mathbf{BE}_{ijmax}$	Maximum battery energy which can be stored in a battery
$\mathbf{BE}_{ijmin}$	Minimum battery energy which can be stored in a battery
$\mathbf{cr}_j$	Charging rate of jth vehicle in terms of fraction it can charge w.r.t new battery
p_s	Probability of event s
D	Difference between Cost of charging with priority and without priority among PEVs

CHAPTER 1

INTRODUCTION

Faced with dwindling fossil fuels and the increasingly negative impact of climate change on society, several countries have instigated national plans to reduce carbon emissions [1]. In particular, the electrification of transport is seen as one of the main pathways to achieve significant reductions in CO2 emissions. In the last few years, PEVs have gained ground. An ambitious target of having 6-7 million electric/hybrid vehicles in India by the year 2020 has been set by the Government of India [2] which shows the major role Electric Vehicles will play in the transportation system.
Importance of Electric vehicle is evident throughout the history. First EVs were introduced shortly after the invention of lead-acid batteries and by late 1800s electric motors were also introduced. However, due to limitations on heavyweights, short trip range, long charging time and durability of storage units, EVs could not sustain in the market([3]). Search for sustainable means of transportation have brought back the EVs

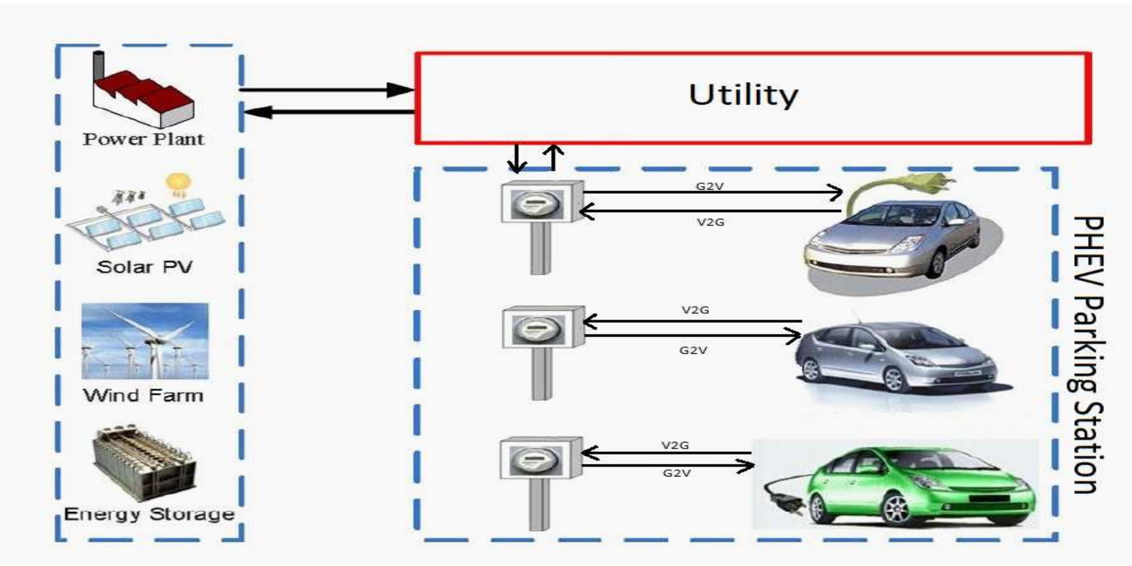

Figure 1.1: Charging Infrastructure for PEVs

into the limelight and advancements in PEV technology have removed the disadvantages associated with it to a large extent. But still, a lot of research is needed to have a complete transition from fossil fuel based vehicles to Electricity based vehicles.

In order to ensure that the large-scale deployment of EVs results in a significant reduction of CO2 emissions, it is important that they are charged using energy from renewable sources (e.g., wind and solar). Crucially, given the intermittent nature of these sources, mechanisms (e.g., [4] and [5]), as part of a smart grid [6], need to be developed to ensure the smooth integration of such sources in our energy systems. EVs could potentially help by storing energy when there is a surplus and feed this energy back to the grid when there is demand for it [7], [8]. Indeed, the ability of EVs to store energy while being used for transportation [9] represents an enormous potential to make energy systems more efficient. On the one hand, given that vehicles drive only for a small percentage of the day (4%-5%) and a large percentage of the vehicles stay unused in parking lots (9̃0%) (Data of US) [10] , and considering the fact that EVs are equipped with large batteries, they could be used as storage devices when parked (i.e., as part of vehicle-to-grid (V2G) schemes) [7] and, thus, dramatically increase the storage capacity of the network. Studies like [7] have shown that if one-fourth of the vehicles in the US were electric, this would double the current storage capacity of the network. On the other hand, given that large numbers of EVs need to charge on a daily, if EVs charge as and when needed, they may overload the network. For this reason, new mechanisms are required to be able to manage the charging of EVs grid-to-vehicle (V2G) in real time while considering the constraints of the distribution networks within which EVs need to charge.

A large-scale deployment of PEVs into existing distribution system will bring opportunities and challenges [11] for the power grid. The uncoordinated and random charging of PEVs can increase the peak load demand of power grid if smart charging techniques are not utilized. The PEV users may want to prioritize charging their vehicles. Also, as PEVs will be connected to a low voltage distribution system, it can overload the distribution transformers and distribution lines during charging. However, as a stationary PEV can act like a battery and can be used to store and provide electricity during peak demand hours, large-scale use of PEVs can supplement grid power by the V2G operation. Also, it can provide ancillary services such as spinning reserves, voltage profile regulation, demand-side management, system optimization and frequency regulation as discussed in [12] & [13].A collection of PEVs not in operation, like in a parking station(both commercial and residential), with the help of an aggregator, can participate in above-mentioned activities and can reduce their operational cost in the process. The priority of the PEVs can be of two type:

1. **System generated**: which depends on the battery energy level and duration of parking of the vehicle in the parking slot
2. **User Defined**: User can add weight to the priority to be given to the PEV in charging scheduling according to their requirements.

Because of these priorities, the aggregator may not be able to optimize the charging scheduling operation and thus incurs losses, which ultimately is to be borne by the users. In order to compensate for the losses, there should be an extra premium, according to user's demands, to be levied upon users to compensate for the losses.

1.1 Literature Review

In recent years, various charging strategies, considering only the G2V mode, have been proposed in the literature that can reduce the impacts of PEVs on the power system [14]-[17]. In [18] and [19], a charging strategy allowing PEVs to either operate in G2V or V2G mode is presented to study the impact of different PEV penetration levels on various aspects of distribution network such as voltage security and power losses.The major limitation of studies [14]-[19] is that the PEV operation is allowed in a single mode (G2V or V2G) only.In [20], authors have investigated the problem of how to regulate the collective charging load of a large fleet of plug-in electric taxis (PETs) in a metropolis from the viewpoint of the utility company. Because the charging load of PET is much higher and less predictable compared with common private electric vehicle, the unregulated charging load of PET fleet can potentially bring large and unpredictable peaks to the distribution system and cause severe damage. To address this problem, this paper proposes a real-time pricing mechanism that can successfully regulate the collective charging load to track a given load profile. The mechanism design consists of three steps. First, two aggregated models are proposed for PET fleet to characterize, separately, the relationship between charging decisions of the fleet and real-time prices, and the relationship between energy dynamics and charging decisions of the fleet. Then, an optimization problem is designed to calculate the optimal charging load profile that can be accomplished by the fleet finally; an efficient online method is launched to calculate proper real time prices, such that the collective charging load of fleet can track the desired value as the response to the prices.The paper took viewpoint of utility company, and tries to regulate the collective charging load of PET fleet by setting proper electricity prices in real time, so that the total charging load can track a desired profile.As for commercial vehicles, maximum emphasis is on maximizing the energy stored, so V2G operation is not taken into account.The focus is on maximizing the combined energy stored in fleet ,due to commercial nature of the vehicles.The process is optimized only for G2V energy transfer and take energy of whole fleet as maximizing variable.There is no mention of priority and premium associated with it.

In [21] - [28] charging strategies have considered V2G and G2V operations for optimal scheduling of load, but studies are not comprehensive.The role of aggregator coordinating charging of PEVs is manifold.It not only should provide a monetary benefit to PEV owner for V2G operation and assist in flattening of load curve by V2G and G2V operation, but also should prioritize the charging schedule on the basis of user's demand and also should be able to set premium to be levied from user for their PEV's priority charging.

The authors in [21]-[24], have considered objective functions to minimize the total energy cost for users using G2V and V2G operations but they have not taken into account the priority among the PEVs based on their charging level, the duration for which they are parked or the users demand.In [28], authors have used an intelligent Artificial Neural network (trained using household power consumption and EV energy demand data), to decide when the V2G and V2G operations should occur. The data come from logged data in Smart Meters. The ANN is a two-layer feed-forward network with sigmoid neurons in the hidden layer and soft-max neurons in the output layer, which can classify vectors, notably when EVs need to perform the V2G or V2G operation. Performance is evaluated using confusion matrix and ROC curves.However, network constraints are not taken into account and decision is based only on energy requirement of the household, not on dynamic pricing to reduce the charging cost.In [25] two charging strategies are proposed using G2V and V2G operation and take into account technical and economic aspects of charging the PEV, but they have also not taken into account the priority among PEVs.In [26], authors have developed an online intelligent decision making strategy that enables aggregators in public parking lots to dynamically manage PEV charging, based on prioritizing PEVs in order to determine the order in which they are charged. The priorities are based on designing a fuzzy expert system for the aggregator using PEV attributes, including the SOC, battery capacity, charger max power rating, and departure time of the vehicle. Case studies are simulated for a typical distribution system with different parking lots. Using proposed scored priority, they have tried to incorporate critical PEVs energy demand, by making them top priority as they have short parking duration and high charging time. The proposed solution also benefits from a simple and fast implementation algorithm. However, there is a need for quantitative measure/regulation to reveal how much the aggregator fails to satisfy all the PEVs. Such measure needs to employ a monetary penalty scheme, which is underdeveloped by the authors as a future extension and contribution of this study.Apart from this, the introduction of priority on the basis of the user is also not studied. Also, the charging aspect of EV is taken into account and is maximized, however, the cost of charging and V2G operations are not taken into account, which can be used for Demand response and better load profile.In [27] authors have taken into account priority into charging scheduling, but priority calculations don't involve user's priority demand.Also, no extra premium /penalty is imposed based on priority.

To analyze the benefits of optimal charging, a game theoretic based multi-agent DR simulation platform called Okeanos was used in [29], which showed that EV penetration and feed-in tariffs if increased, can lead to the reduction in utility bills. In [30] and [31], simple demand response strategy is used to curtail and shift the high power household appliances (including EVs) based on the demand limits, user's priority, and comfort preference.EVs are considered only as a load and hence there is only G2V operation.

In this project, intelligent charging scheduling of PEVs stationed in parking stations is performed for optimal integration within existing distribution system infrastructure.The optimization methodology involves posing the problem as Non-Linear Programming problem(NLP) and converting it into mixed integer linear programming problem (MILP), which is solved using GAMS. The charging scheduling tries to provide a solution for priority charging as well.The main contribution of project are as follows:

a) Intelligent charging strategy is proposed in a dynamic day-ahead pricing scenario which aims at G2V operation in lesser tariffs slots and provides a monetary benefit to PEV owner by the V2G operation.The developed strategy is based on minimizing total cost of charging and the priority among PEVs.The priority is a function of remaining battery energy, the duration for which the vehicle will be parked and user-defined priority called as Weight.

b) A strategy is developed to calculate premium which can be levied on User's depending on "Weight" they assign to their respective PEVs for priority charging .

1.2 Objective

The main objectives of the project can be enumerated as follows:

1. Formulate an intelligent charging scheduling strategy for Plug-in Electric Vehicle(PEV) incorporating a unified grid-to-vehicle(G2V) and vehicle-to-grid(V2G) charging framework by posing it as an optimization problem.
2. Incorporate Users' & PEVs' priority based on duration of parking and state of battery energy into optimization algorithm and formulate the problem into linear problem to find global optimal solution. With help of Monte Carlo Simulation, formulate a strategy to calculate premium for user defined priority.
3. Test the model for 5 PEVs for different scenarios :
   (a) Same Battery capacity and charging rate
   (b) Different charging rates
   (c) Different charging rates and different battery capacity

1.3 Scope Of Work

In this project, a residential PEV parking station is considered which is capable of energy flow in both directions and is associated with an aggregator which participates in energy market on behalf of PEV owners. It is considered that charging can be controlled by the charging station depending on instructions provided by aggregator during a period of 24 hours. The charging is scheduled by the aggregator on the basis of information provided by the PEV owners and do not change for the period under consideration. The charging costs are assessed in G2V & V2G framework and premium is found to be levied on the PEV owners for their Users' priority.

1.4 Overview and Structure of Thesis

In 2^{nd} chapter of the thesis, we will provide a description of different charging methodologies available for PEV and an equivalent circuit of Plug-In Electric Vehicle during G2V and V2G operation

In 3^{rd} chapter, we will provide a definition of the problem involving the priority and without priority scenarios and significance of the study of priority premium calculation for PEVs.

In 4^{th} chapter we will formulate the problem of charging scheduling in the dynamic pricing environment. We will introduce different constraints to be taken into account while charging and also the formulation of priority charging and its association with the cost optimization problem will be given. Conversion of NLP to MILP shall also be discussed

In 5^{th}chapter Detailed description of System under consideration is discussed.Various cases and scenarios under which we are trying to find the charging scheduling and Priority premium determination are also discussed in detail.

In 6^{th} chapter, the solution methodology is discussed providing a process flow diagram, which we are following to find the solution of problem defined in previous chapters.

In 7^{th} chapter we will use the model formulated in the previous chapter and use it on different cases & scenarios for 5 PEV parking station to calculate the premium

In 8^{th} chapter conclusion and inference from the results obtained from intelligent charging schedules of PEVs is discussed. Scope and future work are also discussed.

Summary

In this chapter, importance of PEVs,the problems being faced while using PEVs ,a brief account of research work done in the area of PEV charging scheduling are discussed.Also, objectives of the project,its scope and brief outline of the theis is also provided.

CHAPTER 2

BRIEF DESCRIPTION OF PLUG-IN ELECTRIC VEHICLE

A Plug-In Electric Vehicle consists of many components like Transmission System, Battery packs, Electric Motor, and power electronics system as shown in Fig.2.1 [32].However, when the vehicle is parked and is performing V2G or G2V operation, then it is essentially using the battery pack, charging control system and power electronics system.so in this section, a brief description of charging schemes of batteries and their modeling is discussed.

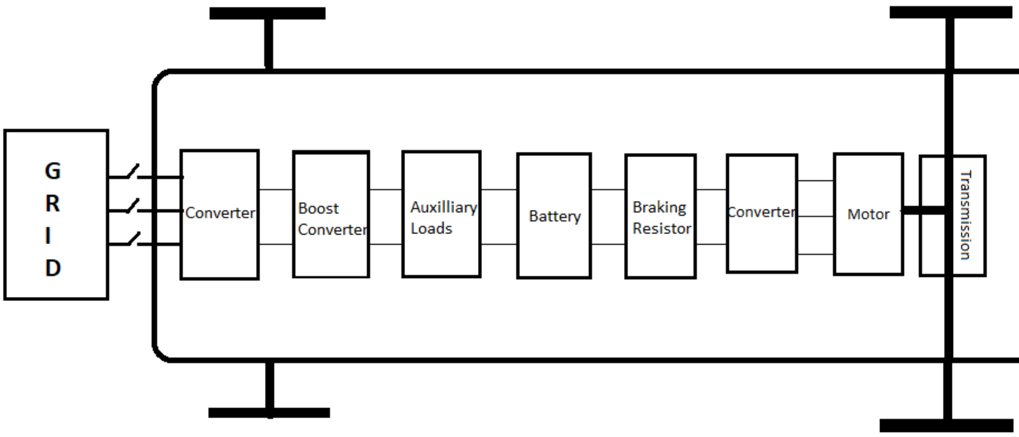

Figure 2.1: Different components of Electric Vehicle

A brief description of different components is as follows:

1.**Converter**: They are used to convert the dc voltage of battery into suitable AC voltage for the functioning of Electric Motor. They control the speed and torque of the motor by changing the frequency and voltage of the output AC. Also, they convert 3 phase supply coming from the grid into DC voltage for storage purpose in the battery.

2.**Boost Converter**: The DC voltage generated by the converter is usually on lower voltage side, which is not suitable for charging the battery properly. Therefore, a boost converter is used to transfer power from low voltage side of the rectifier(converter) to high voltage charging side of the battery.

3.**Auxiliary Loads**: It comprises of different loads which are not directly related to vehicles transmission system like, lights, AC, Interactive consoles, wipers, various sensors placed inside an electric vehicle etc. These loads are not constant as they vary according to user preference and environmental factors.
4.**Battery**: Battery is the main component of a PEV.It is the stores the energy required to run the system. There are many different kinds of batteries available like Lithium Ion, Nickle metal hydride, lead acid etc. While selecting battery different key aspects like internal resistance, charging cycle time, discharging cycle time, maximum power, temperature rise, energy density, specific energy etc., need to be carefully studied for its suitability in a vehicle.
5.**Braking Resistor**: During regenerative braking, the maximum voltage of the battery should not exceed, so breaking resistors are put in place as a precautionary measure.
6.**Motor**: The 3 phase motor, is used to provide traction power for the wheels. It is coupled to the wheels via a transmission system. The usual preferences are Induction Motor(IM), Permanent Magnet Synchronous Motor (PMSM) and Switched Reluctance Motor(SRM). The selection depends upon a number of factors like volume, mass, cost, energy density, maintenance, efficiency, and reliability.
7.**Transmission**: Transmission system provides torque for the left and right wheels which consists differential system having different gear ratio so that it can fit high speed rotating the electric motor shaft to lower speed wheels.

2.1 Charging Schemes for Batteries

The longevity, safety, and durability of battery largely depends on careful charging and discharging as mentioned in chapter 2 of [3].So, its imperative to study different battery charging methods. For EV batteries, following are the methods generally adopted:

1. **Constant Voltage**: As the name suggests, in this scheme battery is charged at a constant voltage. It is suitable for most kind of batteries and is the simplest charging scheme available. The charging current changes and can be high initially and gradually decreases to zero till full charge. However, due to high initial charging current, the initial power requirement is high which is not available in case of residential parking stations.
2. **Constant Current**: The charging voltage is controlled in this scheme to maintain a constant current. The advantage of this method is that state of Charge(SoC) increases linearly with time and hence the battery energy also increases linearly.

But, the problem comes in detecting when the battery is charged to 100%. Different indirect measurements combination like temperature rise, temperature gradient rise, voltage increase and charging time, can be used.

3. **Combination of both**: A combination of constant current and constant voltage can be used for charging the batteries to avoid drawbacks of both type of charging scheme. Initially, if the battery is not pre-charged then a low-value constant current can be used. Then we can switch to constant current charging scheme to reach a threshold value after which, the scheme is changed to a constant voltage. Constant voltage scheme is used to maintain battery voltage afterward.

2.2 Battery Model

Battery modeling is an effective tool and forms basis for battery design, manufacturing, and control. It is important as the model gives us battery characteristics and ways to do effective battery management. Also, logically model development is the first step in developing any systems identification and state estimation algorithm. The battery modeling can be of two types :

1. Capacity Model
2. Equivalent circuit models

For the purpose of EV integration into the grid, its control and optimization, the equivalent electric circuit model with lumped parameters is more favored by the engineers, as the battery terminal voltage, current, temperature, and SOC are more of interest than the detailed electrochemical reactions inside the battery.[32]

2.2.1 Electric Model

Here we are considering steady state model, neglecting the dynamic behavior.The electric equivalent circuit diagram can be seen as in Fig.2.2.The battery model consists of a voltage source $V_{Bat,int}$, two inner resistances $R_{Bat,dis}$ and $R_{Bat,cha}$ for discharging and charging respectively. Two diodes are ideal and being used for symbolic purpose only i.e., to shift from discharging to charging resistances.i_{Bat} is the current flowing through the circuit, which can be considered as positive for discharging and vice-versa for charging, as battery is considered to be energy source.$V_{Bat}$is the output voltage developed by the battery while discharging or the voltage applied to battery for charging. The $R_{Bat,dis}$

and $R_{Bat,cha}$ and $V_{Bat,int}$ depends upon the SoC of the battery(which is defined as ratio of energy stored to maximum storage capacity of the battery) at a particular instant and thus make the voltage V_{Bat} during discharging dependent on SoC.

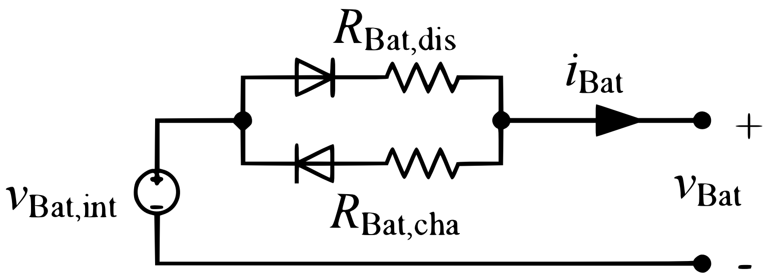

Figure 2.2: Electric equivalent circuit diagram of a battery

From the Fig.2.2, we can find the output voltage as :

$$V_{Bat} = \begin{cases} V_{bat,int} \text{ - } R_{Bat,dis} i_{Bat} & \text{for } i_{Bat} \geq 0 \\ V_{bat,int} \text{ - } R_{Bat,cha} i_{Bat} & \text{for } i_{Bat} < 0, \end{cases} \tag{2.1}$$

The inner voltage and the two resistances depends on the SoC and hence varies with time.

2.2.2 Capacity Model

The inner source voltage, discharging resistance and charging resistance ,all depends on SoC. State-of-Charge depends on integral of equivalent current drawn or supplied to the battery :

$$SoC_{Bat} = SoC_{Bat,ini} + \frac{1}{Ah\ Capacity} \int_0^T i_{Bat,eq} dt \tag{2.2}$$

Here,

SoC_{Bat} : SoC of Battery at time T

$SoC_{Bat,ini}$:Initial SoC of Battery

$i_{Bat,eq}$:Equivalent battery current in Amps[A]

The equivalent current of battery depends on the sign of the current flowing.So,

$$i_{Bat,eq} = \begin{cases} I_{Bat,1}(\frac{i_{Bat}}{I_{Bat,1}})^k & \text{for } i_{Bat} \geq 0 \\ \eta_{Bat,cha} i_{Bat} & \text{for } i_{Bat} < 0 \end{cases} \tag{2.3}$$

Here, $I_{Bat,1}$ is the nominal 1 hour discharge current.

$$k = \begin{cases} 1 & \text{for } i_{Bat} \leq I_{Bat,1} \\ 1.125 & \text{for } i_{Bat} > I_{Bat,1} \end{cases} \tag{2.4}$$

where

k: Peukert Number

$\eta_{Bat,cha}$: Charging Efficiency of the battery

Depending on the value of discharging current, the Peukert Number has two different values. If the current is higher than $I_{Bat,1}$ then the capacity is reduced significantly. From Eq.2.2, we can say that Δ SoC i.e., change in SoC of the battery from time T1 to T2, only depends on the integral portion

$$\Delta SoC = \frac{1}{Ah\ \ Capacity} \int_0^T i_{Bat,eq} dt \tag{2.5}$$

If $i_{Bat,eq}$ is considered constant, i.e, in case of constant current charging mode, then Δ SoC only will depend upon Δ t.

$$\Delta SoC \propto \Delta t \tag{2.6}$$

From eq.2.1 and assuming constant current operation we can conclude that :

$$V_{Bat} = f(SoC) \tag{2.7}$$

If we define BE(t) as battery energy at time t,

$$BE(t) = V_{Bat} i_{Bat}(t - t_0) \tag{2.8}$$

then in constant current operation,using eq.2.1 we can say that

$$BE(t) \propto \Delta SoC \tag{2.9}$$

or,

$$BE(t) = BatConst\Delta SoC \tag{2.10}$$

Where, $BatConst$ is constant of proportionality. Hence we can assume Battery energy also as an indicator of SoC. In our analysis, we have therefore used battery energy BE instead of SoC.

Summary

This chapter provided a brief introduction to PEV's different components, the charging strategies used for Battery of PEV.Also, different models for battery of PEV are discussed and it is shown how battery energy is also linearly dependent upon State of Charge.

CHAPTER 3

PROBLEM DEFINITION

We are trying to solve a two-fold problem in this project:

1. Intelligent charging scheduling of Electric Vehicle
2. Priority Premium Determination for Users in parking station

So, this section gives a brief explanation of the problem in PEV charging and its impact on the aggregator.The whole day is divided into 8 time slots (T1-T8).

3.1 Need of Intelligent Charging

Let us consider one PEV(N1), which arrives at parking station in time slot T2 with BE level of say 60% and will remain till T6, as can be shown by its presence matrix(Table.3.1) which is a matrix consisting 0 & 1,0 representing absence of PEV in a particular time slot, and 1 representing presence.

Table 3.1: Sample Presence Matrix for N1 only

	PEV N1
T1	0
T2	1
T3	1
T4	1
T5	1
T6	1
T7	0
T8	0

The cost of electricity in each time slot is as given in Table.3.2.

Let us assume that in one time slot the PEV charges 20% of its BE capacity, and BE capacity be 5kWh, so it should take 2-time slots to charge it to full. However, if the PEV starts charging as soon as it is plugged in and continues to do so, till it charges to

Table 3.2: Sample Electricity Prices for each time slot

Time Slot	Price (Rs/kWh)
T1	10
T2	15
T3	15
T4	8
T5	10
T6	4
T7	6
T8	6

full capacity, the total cost incurred would be 15+15 =Rs 30. However, if the charging schedule is such that depending on prices and BE level, we can defer the charging to T4 & T6 time slots, then also the PEV will be fully charged but now the cost incurred will be 8+6 = Rs 14, so the customer can save significant money by using intelligent charging scheduling, which aims to minimize the cost of charging, depending on the cost of electricity, the duration for which the vehicle will stay and the current status of the BE level.

3.2 Need of Priority Charging & Premium

Let us assume that there are two identical PEVs which are to be charged in a parking station as shown in Figure 3.1. The time of arrival and the remaining battery energy is different for both. Also, the time for which they remain parked in the charging station is different. Under the scenario of dynamic pricing, we have to analyze what happens when we don't put any control over charging of these vehicles and its impact on the aggregator.

Two PEVs can be named as PEV1 & PEV2.To study the impact, we can consider three cases:

1. **First Case**: PEVs charges without any constraint i.e., no V2G no Priority
2. **Second Case**: PEVs charges with the V2G operation only and no priority is imposed upon them.
3. **Third Case**: PEV charges with priority

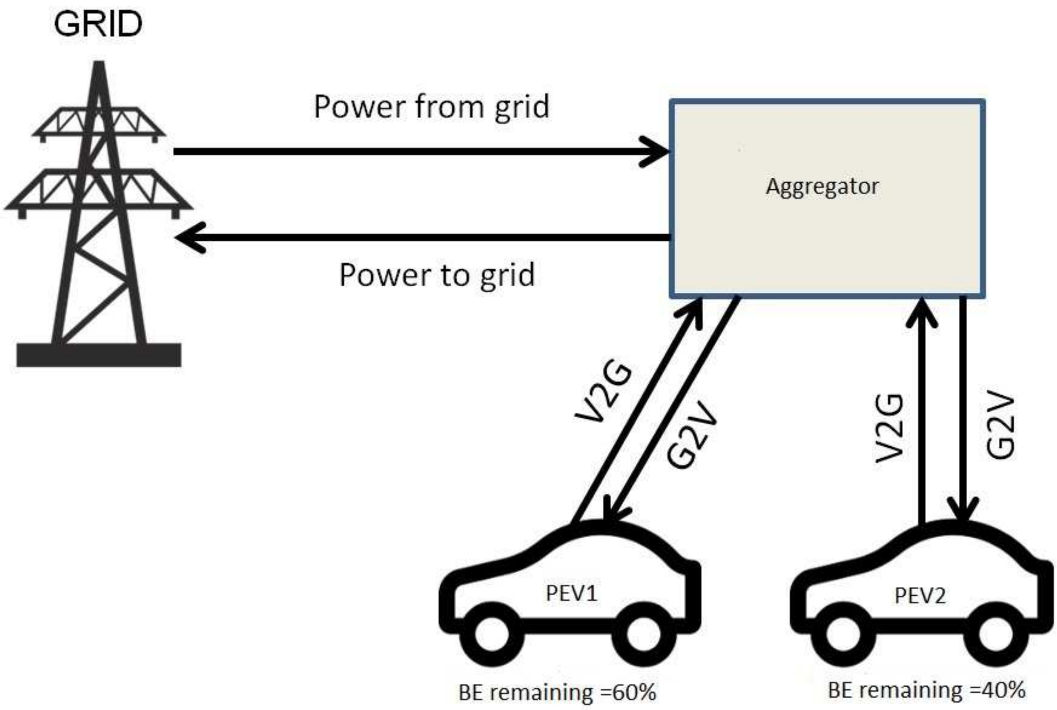

Figure 3.1: Two EVs & their charging infrastructure

3.2.1 PEVs Charges Without Any Constraint

Suppose the PEV1 arrives at T1 with 60% of battery energy remaining and stays in the parking slot till T2 & PEV2 arrives at T1 with 40% of battery energy remaining and stays till T2. Charging rate is 10% of Battery energy /Time slot. The prices of electricity(Rs/kWh) are [T1: 100, T2:10]. In scenario 1, the vehicles will start charging as soon as they arrive. So at the end of T2, PEV1 is at 80% charge and PEV2 is at 60% charge.

Table 3.3: BE of PEV1 Charging Without Any Constraint

Time Slot	Operation	Battery status	Cost(Rs)
T1	G2V	60% to 70%	100
T2	G2V	70% to 80%	10

Table 3.4: BE of PEV2 Charging Without Any Constraint

Time Slot	Operation	Battery status	Cost(Rs)
T1	G2V	40% to 50%	100
T2	G2V	50% to 60%	10

Cost of charging for PEV1=Rs 110 & for PEV2=Rs 110, so Total cost of charging

=Rs 220.

3.2.2 PEVs Charges With V2G Operation

In this scenario all conditions are same as the first scenario except the V2G operation takes place when the 50% battery energy status is achieved. So at the end of time slot T2, PEV1 & PEV2 both are charged to 60%.

Table 3.5: BE of PEV1 Charging With V2G

Time Slot	Operation	Battery status	Cost(Rs)
T1	V2G	60% to 50%	-100
T2	G2V	50% to 60%	10

Table 3.6: BE of PEV2 Charging With V2G

Time Slot	Operation	Battery status	Cost(Rs)
T1	G2V	40% to 50%	100
T2	G2V	50% to 60%	10

Cost of charging for PEV1=Rs -90 for PEV2=Rs 110, so Total Cost of charging =Rs 20.

As compared to the first scenario we can observe that there is a significant reduction in charging cost without compromising the optimal charge level of PEVs.

3.2.3 PEV Charges With Priority & Need for Premium

In this case, we will assume that both the vehicles arrive with same battery energy level but the user has given priority to their PEV to be charged first. Say, PEV1 and PEV2 both have 40% battery energy remaining in their respective batteries. Both will remain for 2 time slots in the parking station.PEV1 has higher priority than PEV2. The prices of electricity are same as scenario 1.

As cost is less in T2 so both should charge in T2.

Table 3.7: BE of PEV1 Charging Without Priority

Time Slot	Operation	Battery status	Cost(Rs)
T1	No operation	40% to 40%	0
T2	G2V	40% to 50%	10

Table 3.8: BE of PEV2 Charging Without Priority

Time Slot	Operation	Battery status	Cost(Rs)
T1	No operation	40% to 40%	0
T2	G2V	50% to 60%	10

Cost of charging for PEV1=Rs 10 for PEV2=Rs 10, so Total charging cost = Rs 20. But when PEV1 has been given priority, it needs to be charged first i.e., in T1.

Table 3.9: BE of PEV1 Charging With Priority

Time Slot	Operation	Battery status	Cost(Rs)
T1	G2V	40% to 50%	100
T2	G2V	50% to 60%	10

Table 3.10: BE of PEV2 Charging With Priority

Time Slot	Operation	Battery status	Cost(Rs)
T1	No operation	40% to 40%	0
T2	G2V	40% to 50%	10

Cost of charging for PEV1=Rs 110 & PEV2=Rs 10, so Total charging cost =Rs 120. Now here,because of user-defined priority, the cost is higher. As a result, the aggregator and other PEV owners incur a loss of opportunity, which needs to be compensated. This demands that the user with high priority should be charged a premium, which can mitigate the cost of loss of opportunity of the aggregator and other PEV owners.

By analyzing both cases, we can conclude that if both problems occur together, the complexity increases and hence there is a need to do further research and come up with a solution to find an optimal solution which can take care of priority as well as cost minimization through intelligent charging scheduling. The solution lies in formulating the problem in such a way that a trade-off or an optimal solution can be achieved and a strategy to compensate for the losses of aggregator, incurred because of non-optimal charging scheduling occurring because of user-defined priorities in the form of a premium.

Summary

This chapter can be used to understand the problem's different aspects like intelligent charging scheduling and its impact on cost of charging.Also, the issue with System's priority and Users' priority are also described taking a simple example.

CHAPTER 4

PROBLEM FORMULATION

The problem we are trying to solve is a two-fold problem as discussed in Chapter 3. In this section we are trying to mathematically formulate the problem along with some constraints so that it can be posed as an optimization problem, where we would like to minimize the objective function, and while doing so, come up with a optimal solution which will allow aggregator to charge/discharge the PEVs and at same time utilize V2G operation to supply electricity back to grid and hence create a business opportunity for himself and the customers he is serving. We will solve the problem for three different scenarios and for each scenario there will be two different cases. Different scenarios can be enumerated as follows:

1. Simplified case, where each PEV is of the same capacity and have same charging rate(Scenario 1).
2. In this case, each PEV is of the same capacity, but their charging rates are different(Scenario 2)
3. This is the general case in which both capacity as well as charging rate of the PEVs are different(Scenario 3)

The details of these scenarios and numerical values of each entity like charging rate, battery capacity will be discussed in subsequent chapters.

For each scenario, the problem will be solved considering priority charging and without considering priority charging. Thus there will be two cases for each scenario.

First of all, we will give formulation for general scenario. Other two can be considered as special cases of it. Also when considering with priority charging and without priority charging, only the objective function will change and the rest of the constraints will remain same.

4.1 Formulation For Different Capacity & Charging Rates

Here, both capacity, as well as charging rate of the PEVs, are different. In the first case we are considering charging with priority, so the objective function can be given as :

$$Objective = min. \sum_{i=1}^{T}\sum_{j=1}^{N}(\frac{U_{G\_Vij}}{\eta_j} - \eta_j.U_{V\_Gij}).P_{ij}.\pi(i) + \sum_{i=1}^{T}\sum_{j=1}^{N}\mu_{ij}.W_j \quad (4.1)$$

Total charging cost is given by :

$$ChargingCost = \sum_{i=1}^{T}\sum_{j=1}^{N}(\frac{U_{G\_Vij}}{\eta_j} - \eta_j.U_{V\_Gij}).P_{ij}.\pi(i) \quad (4.2)$$

subject to:

$$U_{G\_Vij}, U_{V\_Gij}, BE_{i,j} \geq 0 \; \forall i,j \quad (4.3)$$

$$\frac{U_{G\_Vij}}{\eta_j} - \eta_j.U_{V\_Gij} \leq P_{max}.\frac{24}{T}.cr_j \; \forall i,j \quad (4.4)$$

$$\sum_{j=1}^{N}(\frac{U_{G\_Vij}}{\eta_j} - \eta_j.U_{V\_Gij}) \leq maxload \; \forall i \quad (4.5)$$

$$BE_{jopt} \leq BE_{i,j} \leq BE_{jmax} \; \forall i,j \quad (4.6)$$

$$BE_{i,j} = BE_{i-1,j} + U_{G\_Vi,j} - U_{V\_Gi,j} \; \forall i,j \quad (4.7)$$

$$U_{G\_Vij} \times U_{V\_Gij} = 0 \; \forall i,j \quad (4.8)$$

where j is the index for PEVs, i is the index for time intervals, T is the total number of time intervals, N is the total number of PEVs.
$(\frac{U_{G\_Vij}}{\eta_j} - \eta_j.U_{V\_Gij})$ is the total amount of energy bought from the grid during time interval i for jth PEV.U_{G_Vij} is the energy transferred from grid to jth PEV in ith time slot. $\eta_j.U_{V\_Gij}$ is the energy transferred from jth PEV in ith time interval, η_j is the battery efficiency for PEV j, π_i is the price of electricity at time interval i, P_{ij} is the element of a presence matrix and is 1 when the EV is present at the charging station, BE_{ij} is the energy stored in battery for jth EV at ith time interval, P_{max} is the maximum power rating for each charging station, μ_{ij} is the system priority for jth PEV at ith

time interval, d_{ij} is the duration for which jth PEV will remain in parking slot starting at time interval i, BE_{jmax} is the maximum energy that can be stored in the battery for PEV j, BE_{jopt} is the minimum energy level that should be maintained in battery of j thPEV at all times, cr_j is a constant factor representing charging rate as fraction of power it can charge, of the maximum power rating of charging station and $maxload$ is the maximum load which can be connected to grid from parking station.

4.17 represents the constraint on power flow from each charging station to the battery of PEV, plugged in.The energy flow $((\frac{U_{G\_Vij}}{\eta_j} - \eta_j.U_{V\_Gij}))$ depends on two factors: maximum charging power of the charging station(P_{max}) and the charging rate of battery of the PEV(cr_j).

4.37 represents the constraint on energy flow for all charging stations combined.It signifies that the total energy flow from all charging stations combined, cannot exceed the $maxload$ defined by the distribution company for that parking area. Thus it takes care of overloading problem of the distribution system.

Eq.4.41 links battery energy levels with temporal energy flows, the battery energy level of each PEV in present slot depends on the battery energy level at the end of the previous slot as well as the energy flow during the present time slot. 4.19 gives the upper and lower limit for battery energy levels, and Eq.4.8 is to ensure that charging and discharging does not happen simultaneously for any PEV at the same time interval, as a battery cannot charge and discharge simultaneously. The objective 4.1 tries to minimize the total cost of charging and discharging energy stored in the battery of PEV and product of the User's Priority and system's priority, over the period of study. It includes two terms which are summed together to make an objective. The first term represents the total cost of energy flow, either towards battery or from it towards grid and the second term has a product between users' priority(W_j) and systems' priority(μ_{ij}) which treats W_j as weight to amplify the systems' priority μ_{ij} .

The formulation explained above is Non-linear due to Eq.4.8.It is well known that non-linear optimization problems are hard to solve because the non-linear constraints form feasible regions that are difficult to find and the non-linear objectives contain local minima that trap descent-type search methods [33], and hence it is better to convert it to linear optimization problem or Mixed-Integer Linear programming problem so that we can escape from local minima problem. To make the necessary conversion, disjunctive inequality solution method is used which is involves constraining a solution space with

multiple inequalities or sets of inequalities related by an OR statement. This "OR" statement is reformulated using a binary variable as a Big-M reformulation. We have used Big-M formulation as it is a simpler method, requires fewer inequalities as compared to convex hull formulation [34]. The bi-linear problem can be linearized using binary variables & disjunctive inequalities as explained below [35] :
Eq.4.8 can be replaced as:

$$0 \leq U_{G\_Vij} \leq M.(1 - b_{ij}).P_{ij} \tag{4.9}$$

$$0 \leq U_{V\_Gij} \leq M.(b_{ij}).P_{ij} \tag{4.10}$$

where, M is a big positive constant, b_{ij} is a binary variable.
Whenever the binary variable b_{ij} will take value of 1 ,then by equation 4.39, U_{G_Vij} will become 0, and by 4.40, V2G operation will be possible i.e., discharging.The case reverses when b_{ij} is 0. So here, we can observe that the feasibility equation 4.8 is converted from nonlinear equation into two linear equation and therefore we can use MILP solvers to find a globally optimal solution to our problem.

Systems' Priority Calculation

System's priority depends upon the battery energy level BE_{ij}. The EV with lower BE_{ij} should be given priority over others, the duration for which the EV is parked also plays an important role as the EV parked for lesser duration should be given more priority than the one which will remain for a longer period of time when every other parameter is identical for both. So, the systems' priority calculation should combine these both important factors while calculating the priority of EV. Hence, the formulation of the systems' priority can be done as shown in Eq. 4.11:

$$\mu_{ij} = P_{ij}.((BE_{ijmax} + 1) - (d_{ij}/T) - BE_{ij}) \tag{4.11}$$

This priority calculation gives the priority charging to the EV with lower BE levels, through the last term in the objective function. W_j is the priority weight for each PEV, which comes at a premium and is defined by the user.μ_{ij} is high when either the BE_{ij} is low or d_{ij} is low. This high system weight in the last term of 4.1 will ensure that the optimization problem tends to fulfill the charging requirement in the duration for which PEV is available at charging station. W_j is the priority weight associated with each PEV, a higher weight for a PEV will ensure that μ_{ij} reduces significantly during optimization i.e., the vehicle is charged as much as possible within its available duration at the charging station. A lower weight will postpone the charging schedule for that particular PEV, after PEVs with higher weights.

This was the formulation of general case where charging/discharging operation was allowed with priority. To solve the next case , i.e., charging without priority, the objective function becomes:

$$Objective = min. \sum_{i=1}^{T}\sum_{j=1}^{N}(\frac{U_{G\_Vij}}{\eta_j} - \eta_j.U_{V\_Gij}).P_{ij}.\pi(i) \tag{4.12}$$

Total charging cost is given by :

$$ChargingCost = \sum_{i=1}^{T}\sum_{j=1}^{N}(\frac{U_{G\_Vij}}{\eta_j} - \eta_j.U_{V\_Gij}).P_{ij}.\pi(i) \tag{4.13}$$

As there is no priority, the objective function and total charging cost become equal. The constraint equations will remain the same, as they are not affected by priority.

4.2 Formulation for Same Capacity PEV & Different Charging Rates

Here, each PEV is of the same capacity, but their charging rates are different. So the formulation for case of charging with priority can be given as :

$$Objective = min. \sum_{i=1}^{T}\sum_{j=1}^{N}(\frac{U_{G\_Vij}}{\eta_j} - \eta_j.U_{V\_Gij}).P_{ij}.\pi(i) + \sum_{i=1}^{T}\sum_{j=1}^{N}\mu_{ij}.W_j \tag{4.14}$$

Total charging cost is given by :

$$ChargingCost = \sum_{i=1}^{T}\sum_{j=1}^{N}(\frac{U_{G\_Vij}}{\eta_j} - \eta_j.U_{V\_Gij}).P_{ij}.\pi(i) \tag{4.15}$$

subject to:

$$U_{G\_Vij}, U_{V\_Gij}, BE_{i,j} \geq 0 \; \forall i,j \tag{4.16}$$

$$\frac{U_{G\_Vij}}{\eta_j} - \eta_j.U_{V\_Gij} \leq P_{max}.\frac{24}{T}.cr_j \; \forall i,j \tag{4.17}$$

$$\sum_{j=1}^{N}(\frac{U_{G\_Vij}}{\eta_j} - \eta_j.U_{V\_Gij}) \leq maxload \; \forall i \tag{4.18}$$

$$BE_{jopt} \leq BE_{i,j} \leq BE_{jmax} \; \forall i,j \tag{4.19}$$

$$0 \leq U_{G\_Vij} \leq M.(1-b_{ij}).P_{ij} \tag{4.20}$$

$$0 \leq U_{V\_Gij} \leq M.(b_{ij}).P_{ij} \tag{4.21}$$

$$BE_{i,j} = BE_{i-1,j} + U_{G\_Vi,j} - U_{V\_Gi,j} \; \forall i,j \tag{4.22}$$

Symbols and equations have same meaning as described in section 7.1.3.However,as the battery capacity for each PEV is same so, in 4.19, BE_{jmax} is same for all, and hence can be written as only BE_{max}, so Eq.4.19, is modified to :

$$BE_{jopt} \leq BE_{i,j} \leq BE_{max} \; \forall i,j \tag{4.23}$$

For case of charging without priority, the objective function will modify as defined in section 7.1.3 case of charging without priority :

$$Objective = min. \sum_{i=1}^{T}\sum_{j=1}^{N}(\frac{U_{G\_Vij}}{\eta_j} - \eta_j.U_{V\_Gij}).P_{ij}.\pi(i) \tag{4.24}$$

Total charging cost is given by :

$$ChargingCost = \sum_{i=1}^{T}\sum_{j=1}^{N}(\frac{U_{G\_Vij}}{\eta_j} - \eta_j.U_{V\_Gij}).P_{ij}.\pi(i) \tag{4.25}$$

Both charging cost and objective function will be identical. The constraints will be same as defined in this section's case of charging with priority.

4.3 Formulation for Identical PEVs

Here, we are considering that the charging rate of each PEV is same and also the battery capacity. In other words, all PEVs are identical in this scenario. So, the objective function for case of charging with priority among PEVs, the objective function will be :

$$Objective = min. \sum_{i=1}^{T}\sum_{j=1}^{N}(\frac{U_{G\_Vij}}{\eta_j} - \eta_j.U_{V\_Gij}).P_{ij}.\pi(i) + \sum_{i=1}^{T}\sum_{j=1}^{N}\mu_{ij}.W_j \quad (4.26)$$

Total charging cost is given by :

$$ChargingCost = \sum_{i=1}^{T}\sum_{j=1}^{N}(\frac{U_{G\_Vij}}{\eta_j} - \eta_j.U_{V\_Gij}).P_{ij}.\pi(i) \quad (4.27)$$

subject to:

$$U_{G\_Vij}, U_{V\_Gij}, BE_{i,j} \geq 0 \; \forall i,j \quad (4.28)$$

$$\frac{U_{G\_Vij}}{\eta_j} - \eta_j.U_{V\_Gij} \leq P_{max}.\frac{24}{T}.cr_j \; \forall i,j \quad (4.29)$$

$$\sum_{j=1}^{N}(\frac{U_{G\_Vij}}{\eta_j} - \eta_j.U_{V\_Gij}) \leq maxload \; \forall i \quad (4.30)$$

$$BE_{jopt} \leq BE_{i,j} \leq BE_{jmax} \; \forall i,j \quad (4.31)$$

$$0 \leq U_{G\_Vij} \leq M.(1-b_{ij}).P_{ij} \quad (4.32)$$

$$0 \leq U_{V\_Gij} \leq M.(b_{ij}).P_{ij} \quad (4.33)$$

$$BE_{i,j} = BE_{i-1,j} + U_{G\_Vi,j} - U_{V\_Gi,j} \; \forall i,j \quad (4.34)$$

Symbols and equations have same meaning as described in section 7.1.3.As we are considering identical PEVs, so a couple of constraint equations (4.29 & 4.31) will change.

Following will be the new set of constraints :

$$U_{G\_Vij}, U_{V\_Gij}, BE_{i,j} \geq 0 \; \forall i, j \tag{4.35}$$

$$\frac{U_{G\_Vij}}{\eta_j} - \eta_j.U_{V\_Gij} \leq P_{max}.\frac{24}{T} \; \forall i, j \tag{4.36}$$

$$\sum_{j=1}^{N} (\frac{U_{G\_Vij}}{\eta_j} - \eta_j.U_{V\_Gij}) \leq maxload \; \forall i \tag{4.37}$$

$$BE_{jopt} \leq BE_{i,j} \leq BE_{max} \; \forall i, j \tag{4.38}$$

$$0 \leq U_{G\_Vij} \leq M.(1 - b_{ij}).P_{ij} \tag{4.39}$$

$$0 \leq U_{V\_Gij} \leq M.(b_{ij}).P_{ij} \tag{4.40}$$

$$BE_{i,j} = BE_{i-1,j} + U_{G\_Vi,j} - U_{V\_Gi,j} \; \forall i, j \tag{4.41}$$

It is to be noted that in Eq.4.36, the constant cr_j is dropped and in Eq.4.23 , BE_{jmax} has become BE_{max} , to align the constraints to our assumptions.

For case of charging of PEVs without priority among them, both charging cost and objective will become equal :

$$Objective = min. \sum_{i=1}^{T} \sum_{j=1}^{N} (\frac{U_{G\_Vij}}{\eta_j} - \eta_j.U_{V\_Gij}).P_{ij}.\pi(i) \tag{4.42}$$

The constraint equations will remain same as in previous case of this scenario.
The optimization problem formulated in above three scenarios are run for 2 cases of each of the three scenarios and for a presence matrix. As it is well known that the event of arrival and departure of PEVs is stochastic in nature [36, 25], we cannot get an accurate estimate of charging cost with just one presence matrix. So presence matrix is the stochastic variable in our study. Since presence matrix is uncertain, a Monte Carlo Sampling-Based Method for Stochastic Optimization [37] is run to get an estimate of charging cost as follows:

$$E[Charging\ Cost] = \sum_{s} Charging\ Cost_s.p_s \tag{4.43}$$

where, s is the index of event in stochastic optimization, and p_s is the probability of event s.

Summary

In this chapter the formulation of objective function along with constraints and NLP to MILP reformulation is discussed, which will be used to solve different scenarios in subsequent chapters to find out the premium and intelligent charging scheduling of the PEVs

CHAPTER 5

SYSTEM UNDER STUDY

In this work, a group of 5 PEVs which can be parked in a parking station is considered. PEVs are named as N1-N5 and have different battery capacity and charging rates.

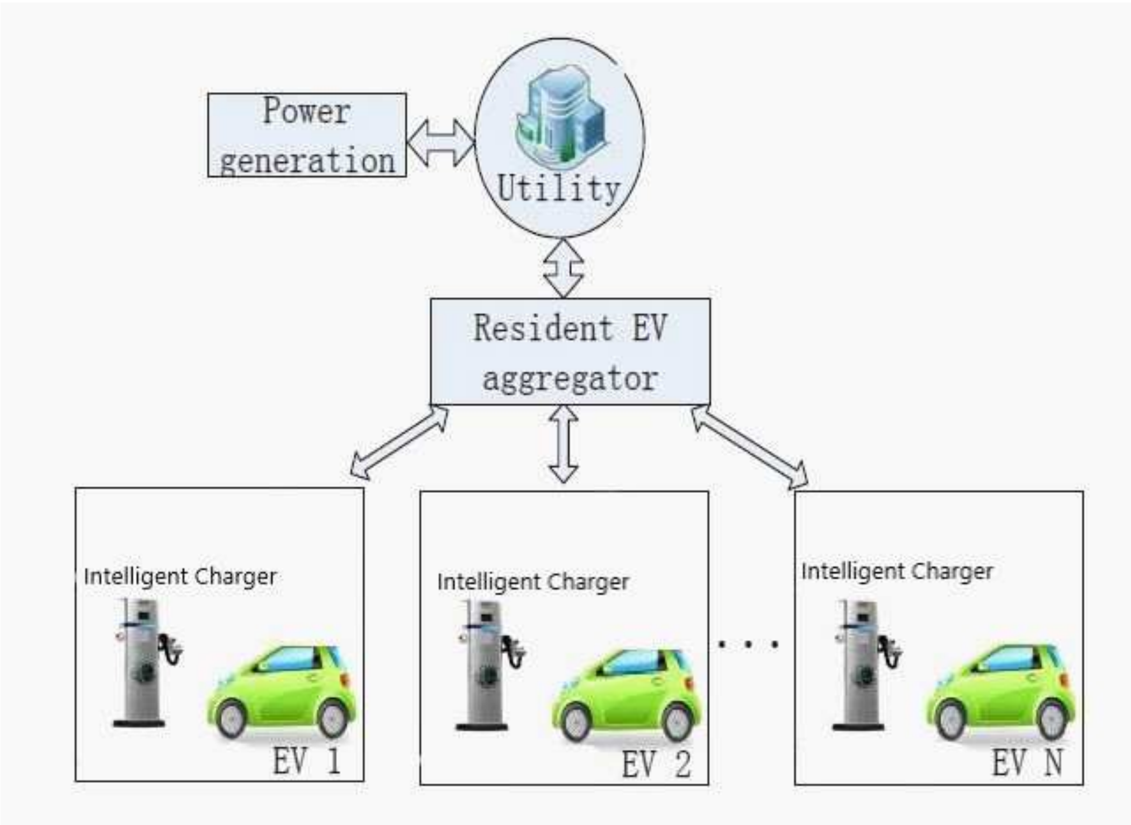

Figure 5.1: Schematic of charging process

Battery capacity is in kWh and the charging rate is defined as a fraction of maximum power a charging plug can deliver (5 kW). It is assumed different because of difference in battery make and their conditions. Battery capacity and charging rates are as given in Table 5.1[38]

The problem is solved for three scenarios:

1. Simplified scenario, where each PEV is of same capacity 13.5 kW and have same charging rate of 5 kW. These parameters are taken for standard TeslaPowerwall 2 system.[39]

Table 5.1: PEV Details

PEV No.	Model	Battery Capacity(kWh)(BE_{jmax})	Charging Rate(cr_j)
N1	Chevy Volt	16	0.55
N2	Smart Fortwo ED	16.5	0.35
N3	Mitsubishi iMiEV	16	0.15
N4	BMW i3	22	0.95
N5	Tesla S	70	0.8

2. Each PEV is of the same capacity, but their charging rates are different, as given by column 3 of Table 5.1.Charging rates were obtained from a random number generator for normal distribution between [0,1].

3. General scenario in which both capacity as well as charging rate of the PEVs are different, with values as given by Table 5.1.These values are taken from commercially available EV data from [38].

The presence of an electric vehicle in the parking spot is dictated by a presence matrix consisting of labeled rows representing Time slot and labeled columns representing PEV, and each entry will be binary with 1 representing the presence of vehicle and 0 as the absence of PEV. Vehicle In-Out instances and duration of parking are taken to be a normal distribution, and different presence matrices are generated accordingly. One such Presence matrix is shown in Table 5.2

	N1	N2	N3	N4	N5
T1	1	1	1	1	1
T2	1	1	1	1	1
T3	0	1	1	1	0
T4	0	0	1	1	0
T5	0	0	0	0	0
T6	0	0	0	0	0
T7	0	0	0	0	0
T8	1	0	1	0	1

Table 5.2: Presence Matrix P1 for event(s=1)

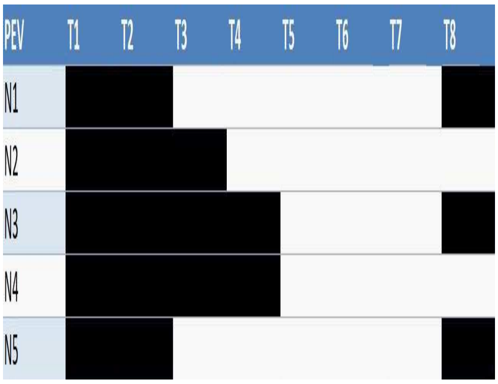

Figure 5.2: Availability of PEV according to Presence Matrix P1

Fig.5.2, shows the availability of PEVs in a residential parking station on the basis of the presence matrix P1.Here we can observe that in time slot T1 & T2 ,all PEV are present.In T3, PEV N1 & N5 leaves and come back in T8.Similarly mobility of other PEV can be observed from the Figure.

The duration matrix corresponding to presence matrix given in Table.5.2 can be given as:

Table 5.3: Duration Matrix for P1

	N1	N2	N3	N4	N5
T1	2	3	4	4	2
T2	1	2	3	3	1
T3	0	1	2	2	0
T4	0	0	1	1	0
T5	0	0	0	0	0
T6	0	0	0	0	0
T7	0	0	0	0	0
T8	3	0	5	0	3

Here, in each cell, the total duration for which the PEV will remain till it departs is tabulated.Like in PEV N1 in time slot T1 , will remain there for Two Time slots(T1&T2) so 2 is written in the cell corresponding to it.Similarly for others. For other events, the presence matrices and the duration matrices are given in Appendix.

As discussed in 4, the presence matrix is a stochastic variable .So some probability value should be assigned to each of the events, for which presence matrices are tabulated , in order to do the cost estimation ,formulated by Eq.4.43.

Various studies like [36, 16, 25] have concluded, that the duration for which PEVs are parked ,follows truncated Normal Distribution, it is assumed that the arrival and departure also follow Normal distribution.So probabilities for different events (s=1 to s=11) can be tabulated as in Table.5.4 The probability p_{Nj} is the probability for PEV Nj for a

Table 5.4: Probabilities for each event

Event	p_{N1}	p_{N2}	p_{N3}	p_{N4}	p_{N5}	p_s
s=1	0.9	0.85	0.9	0.8	0.85	0.47
s=2	0.05	0.85	0.9	0.8	0.85	0.03
s=3	0.9	0.075	0.9	0.8	0.85	0.04
s=4	0.9	0.85	0.05	0.8	0.85	0.03
s=5	0.9	0.85	0.9	0.1	0.85	0.06
s=6	0.9	0.85	0.9	0.8	0.075	0.04
s=7	0.05	0.85	0.9	0.8	0.85	0.03
s=8	0.9	0.075	0.9	0.8	0.85	0.04
s=9	0.9	0.85	0.05	0.8	0.85	0.03
s=10	0.9	0.85	0.9	0.1	0.85	0.06
s=11	0.9	0.85	0.9	0.8	0.075	0.04

particular event and is assigned randomly.p_s is the overall probability for the occurrence of the event s and is the product of p_{N1} -p_{N5}.

In order to calculate the priority, we require BE levels and the duration for which PEV will be parked. This duration(d_{ij}) can be represented by duration matrix for each event. The Price of electricity is taken from Nordic Pool market and is as shown in Table5.5

Table 5.5: Electricity Prices in Dynamic Day-Ahead Market

Time Slot	Price (Rs/kWh)
T1	2.93
T2	3.00
T3	4.56
T4	4.59
T5	3.80
T6	3.87
T7	4.40
T8	3.13

The User's priority is defined as weight W_j.For the solution of problem ,consider the weights as tabulated in Table.5.6.

Table 5.6: Weights assigned by user to their PEV

	N1	N2	N3	N4	N5
W	5	2	4	3	1

There are certain assumptions which will be followed for the system while solving the problem.

1. All the calculations are done for a day i.e.,24 hours, and new day begins at 0001hrs.
2. It is assumed that the unit prices are not changed by the operation of the V2G operation
3. The η used for the simulation includes the efficiency of the battery as well as any inverters or converters used along with the battery and we simply state it as efficiency of battery.
4. It is assumed that the Battery Efficiency (η) remains constant with time
5. The charging happens at maximum power rating with constant current

Summary

This chapter gives an account of technical details of the PEVs which will be used in the model.Apart from this ,stochastic variable(Presence matrix) and its structure is discussed.Other data like price of electricity, weights of PEVs and different assumptions involved are also discussed.

CHAPTER 6

SOLUTION METHODOLOGY

Till now ,we have discussed the need for studying the impact of priority and intelligent charging of PEV (chapter 3) & in chapter 5, we have described the parking system, different scenarios and cases under which we want to study the effect of Priority and intelligent charging.The PEVs arrival, their duration of parking and Weights assigned by users' are also described in detail.
Now using all the information and assumptions described in above chapters, we will try to solve the optimization problem and determine the premium to be levied upon users.The methodology used, to come up with a solution for our problem of intelligent charging scheduling and priority premium determination for each PEV is discussed in detail in this section.A brief description of tool and technique used for solving the problem is also discussed.

As described in Chapter 4, the problem is formulated as an optimization problem for different scenarios to minimize the objective function including the cost of charging the PEV and the priority(both System's & User's) under the constraints which ensures that overloading of distribution system, overcharging/undercharging of batteries and feasible operation takes place.To solve the problem, we will use GAMS modeling system and cplex solver.As presence matrices are stochastic, so Monte Carlo Sampling-Based Method for Stochastic Optimization is used to estimate the cost of charging.A brief description on GAMS,cplex solver & Monte Carlo simulation follows :

GAMS

GAMS(**G**eneral **A**lgebraic **M**odeling **S**ystem) is a high-level modeling system for mathematical programming and optimization.Different type of optimization problems like linear, nonlinear, and mixed-integer can be modelled and solved effectively in GAMS. The system is tailored for complex, large-scale modeling applications and allows the user to build large maintainable models that can be adapted to new situations. The system is available for use on various computer platforms. Models are portable from one platform to another [40]. Advantages of using GAMS are as follows [41]:

1. Access to a large set of existing solution algorithms.So the user is not constrained to use a particular solver, and many different solvers can be tried without changing the formulation.

2. Another important feature of GAMS is independence between model formulation and the model data which means that GAMS allows to formulate the model without direct reference to a specific data set and therefore enables to use the same model code with different data sets or different aggregations of the same data set.So, the model may increase dramatically in size with a new data set, but the formulation remains the same.

3. The model representation in GAMS closely follows the way a model is written using mathematical symbols.It helps in better understanding of model and allows to change the code simply and safely ,without creating lots of errors.

4. GAMS is flexible with respect to both computer type and user interface ,so it can be used on different platforms easily.

5. It can be used together with many other programs like built-in GDX-utility (GDX stands for GAMS Data Exchange) for interfacing with Microsoft Excel.There are many utilities developed and contributed by other GAMS modelers which can provide interface with other software.

Because of the numerous benefits and ease of writing formulation for solving problem in GAMS, it is becoming quite popular among scientific community .In our literature survey,[26] has used GAMS to optimize the priority scores they got from fuzzy expert system.

CPLEX Solver

CPLEX was the first linear optimizer commercially distributed by IBM,which was written in C language. It gave operations researchers unprecedented flexibility, reliability and performance to create novel optimization algorithms, models, and applications [42]. The Simplex algorithm, invented by George Dantzig in 1947 became the basis for the entire field of mathematical optimization and provided the first practical method to solve a linear programming problem. CPLEX evolved over time to embrace and become a leader in the children categories of linear programming, such as integer programming, mixed-integer programming and quadratic programming, too. Now it is one of the most used solver for solving MILP problems also.For solving MILP, CPLEX uses Branch &

Cut Method [43], which is based on Branch & Bound Method, a well known algorithm to solve MILP problem, by solving a sequence of linear relaxations to provide bounds. Mathematically, if general MILP formulation is given by :

$$Z(X) = min.\ cx + fy : x, y \in X \tag{6.1}$$

where

$$X = (x, y) \in \Re^n_+ + 0, 1^n : Ax + By \geq b \tag{6.2}$$

Then, the relaxation can be given as

$$Z(P_X) = min.\ cx + fy : x, y \in X \tag{6.3}$$

where

$$X = (x, y) \in \Re^p_+ + \mathbf{[0,1]}^p : Ax + By \geq b \tag{6.4}$$

The linear relaxation in Eq.6.4 provides a lower bound on the optimal objective value as

$$Z(P_X) \leq Z(X) \tag{6.5}$$

Monte Carlo Simulation

Monte Carlo simulation is used to build models of possible results by substituting a range of values for any parameter or variable that has inherent uncertainty. It then calculates results over and over, each time using a different set of random values from some probability distribution which the variable follows or is assumed to follow. Then it produces distributions of possible outcome values.In this way, Monte Carlo simulation provides a much more comprehensive view of what may happen.

Monte Carlo simulation provides a number of advantages over deterministic, or single-point estimate analysis [44]:

1. Results show not only what could happen, but how likely each outcome is.
2. Because of the data a Monte Carlo simulation generates, itâĂŹs easy to create graphs of different outcomes and their chances of occurrence.
3. With just a few cases, deterministic analysis makes it difficult to see which variables impact the outcome the most. In Monte Carlo simulation, itâĂŹs easy to

see which inputs had the biggest effect on bottom-line results.

4. In deterministic models, it's very difficult to model different combinations of values for different inputs to see the effects of truly different scenarios. Using Monte Carlo simulation, analysts can see exactly which inputs had which values together when certain outcomes occurred.

5. In Monte Carlo simulation, it's possible to model interdependent relationships between input variables. It's important for accuracy to represent how, in reality, when some factors goes up, others go up or down accordingly.

The solution is found for each of the three scenarios defined in section 5 using GAMS, for the objective function which includes priority and excludes priority. Monte Carlo simulations are performed over uncertain presence matrices. Each presence matrix is assigned some probability based on the fact that each PEV's Arrival & Departure follows a Normal distribution [25]. The difference is found between the estimates of "Cost of charging with priority" & "Cost of charging without priority", and the estimated difference is levied upon the PEV owners in proportion to their priority weight demanded. The methodology can be summed up in the form of flow chart(Fig.6.1) as follows:

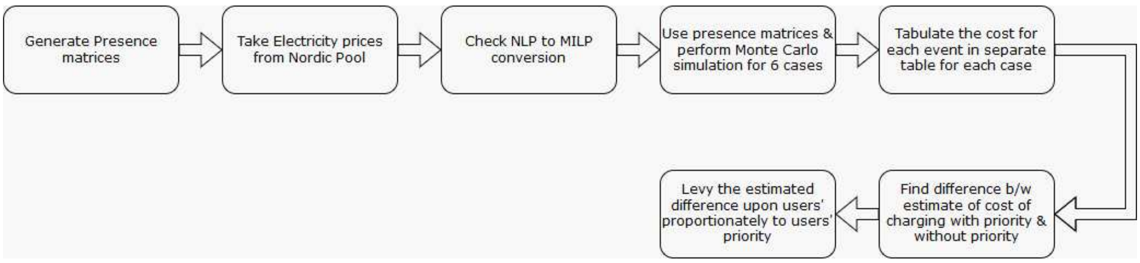

Figure 6.1: Flow chart of solution methodology

Summary

The methodology of solving the problem and different tools used for solving the problem are discussed in this chapter.

CHAPTER 7

RESULTS & OBSERVATIONS

7.1 Results of Model Solution

In this section, the result of the solution obtained from cplex solver used in different scenarios ,as discussed in earlier sections are presented.

Before presenting the results of solution,result of NLP to MILP conversion is presented, as performed for one of the cases.

As can be observed solution report from Fig.7.1,the solver reports Model Status as Optimal, whereas in Fig.7.2, the solver reports Model Status as Locally Optimal , which clearly shows that by performing the conversion of NLP to MILP, we are getting globally optimal solution and hence the formulation modification done from Eq.4.8 to Eq.4.39 & Eq.4.40 is appropriate.

There are six cases:3 scenarios each of which has 2 sub-cases: A).with priority charging and B).without priority charging; and for each case there are 11 events (depending on different Presence matrix) for which optimization problem is solved ,cost of charging and charging scheduling is obtained. For scenario i, the two cases are called as case iA, case iB .For each of the case,results are shown for the event having maximum probability and then using all the events and the costs associated with them,priority premium is estimated.There are 7 variables which will change :

1. objective
2. cost
3. U_{G_Vij}
4. U_{V_Gij}
5. BE_{ij}
6. b_{ij}
7. μ_{ij}

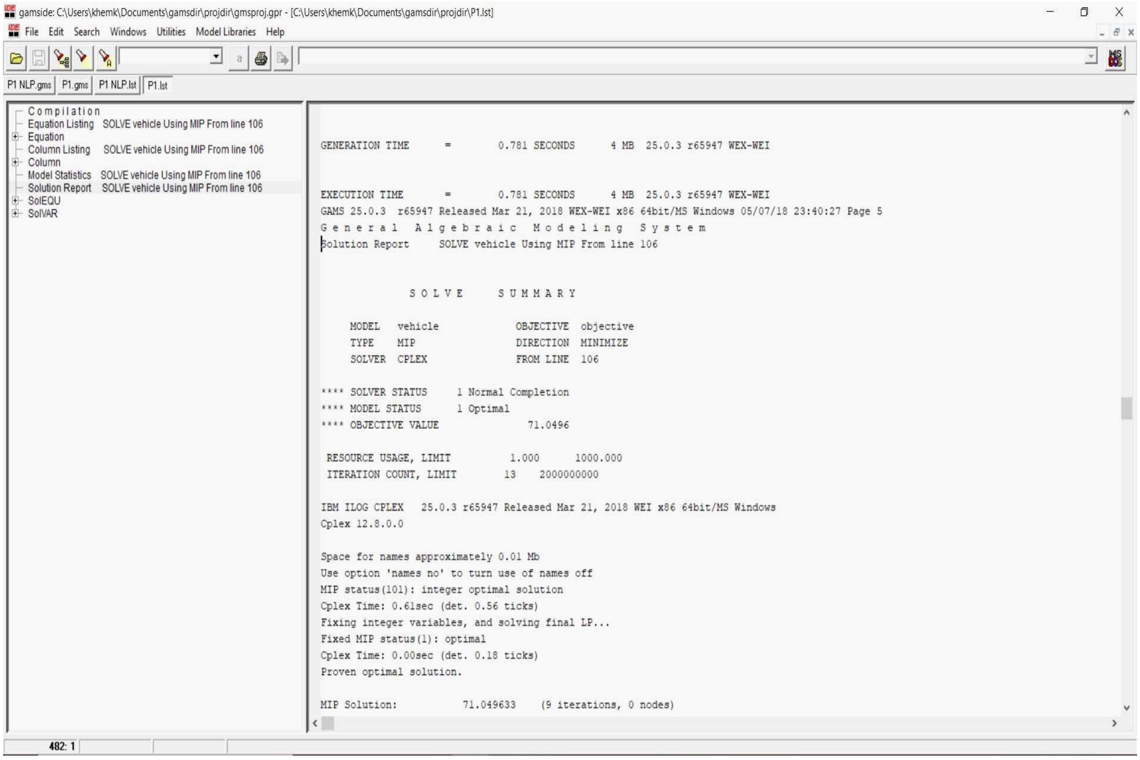

Figure 7.1: Solution report for GAMS solution of MILP solution of one of the cases

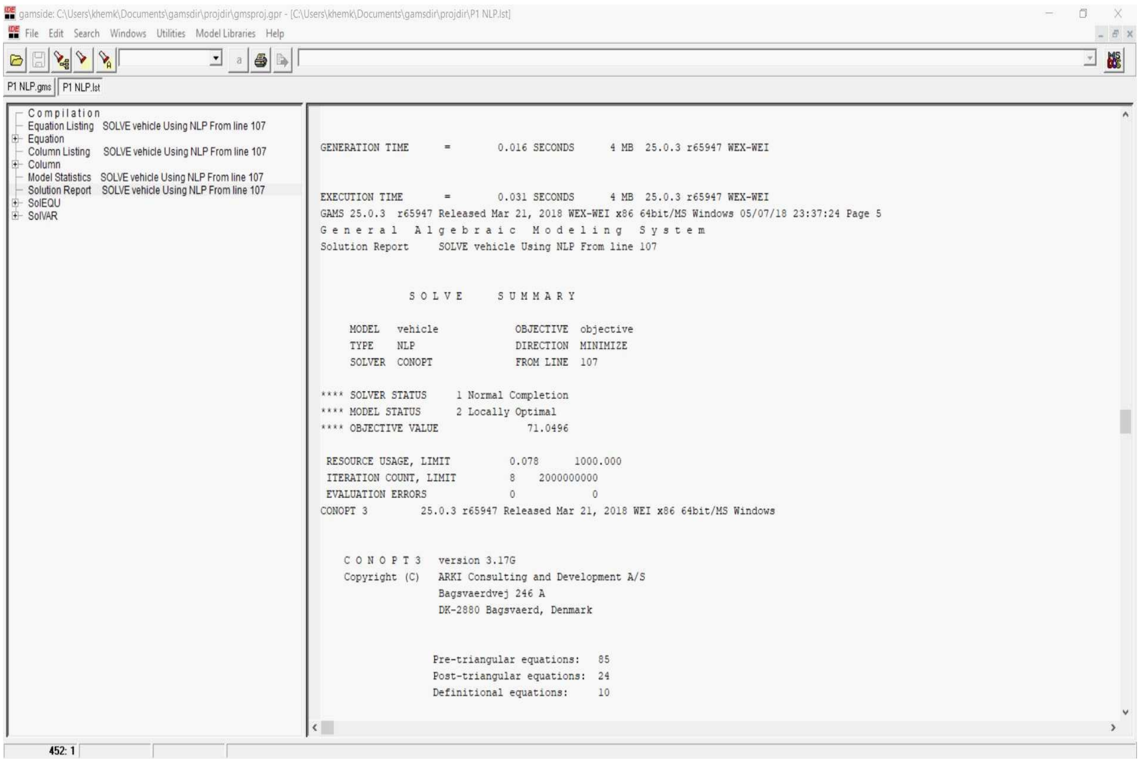

Figure 7.2: Solution report for GAMS solution of NLP solution of one of the cases

We are showing the results of above mentioned variables for event dictated by presence matrix P1, given by Table.5.2 and Duration matrix by Table.5.3

7.1.1 Results for Identical PEVs Charging

It is simplified case, where each PEV is of the same capacity and have same charging rate as discussed in previous chapters.

Charging happens with priority among PEVs

1. **Objective**: The objective function value is found to be :71.05
2. **Cost**: Charging cost is found to be :Rs.139.28
3. **U**$_{G\_Vij}$:The Energy consumed from Grid to vehicle for different vehicles and for different time slot can be shown through Fig.7.3

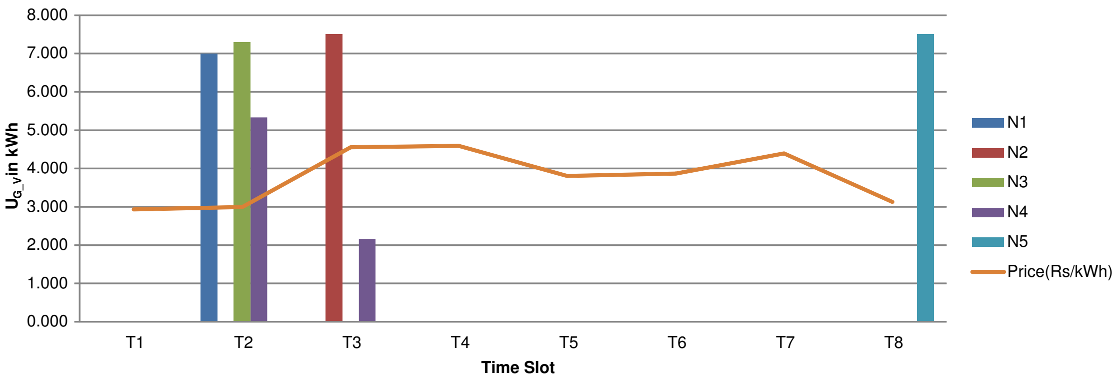

Figure 7.3: U_{G_V} for Identical PEVs charging With Priority

4. **U**$_{V\_Gij}$:The Energy consumed from vehicle to grid for different vehicles and for different time slot can be shown through Fig. 7.4
5. **BE**$_{ij}$:The battery energy level of each PEV for case 1A, for full schedule can be shown in the form of a table 7.1.It is worth noting that when the PEV is not present the BE level is represented as the BE level of previous slot.

Table 7.1: BE$_{ij}$ for Identical PEVs charging With Priority

	N1	N2	N3	N4	N5
T1	6.50	7.67	6.20	6.00	8.00
T2	13.50	6.00	13.50	11.34	6.00
T3	13.50	13.50	13.50	13.50	6.00
T4	13.50	13.50	13.50	13.50	6.00
T5	13.50	13.50	13.50	13.50	6.00
T6	13.50	13.50	13.50	13.50	6.00
T7	13.50	13.50	13.50	13.50	13.50
T8	13.50	13.50	13.50	13.50	13.50

6. **b**$_{ij}$: The variable b is binary, it is 1 when G2V operation takes place and when it is 0 then V2G operation can take place.Table 7.2 shows the value of b for case 1A.

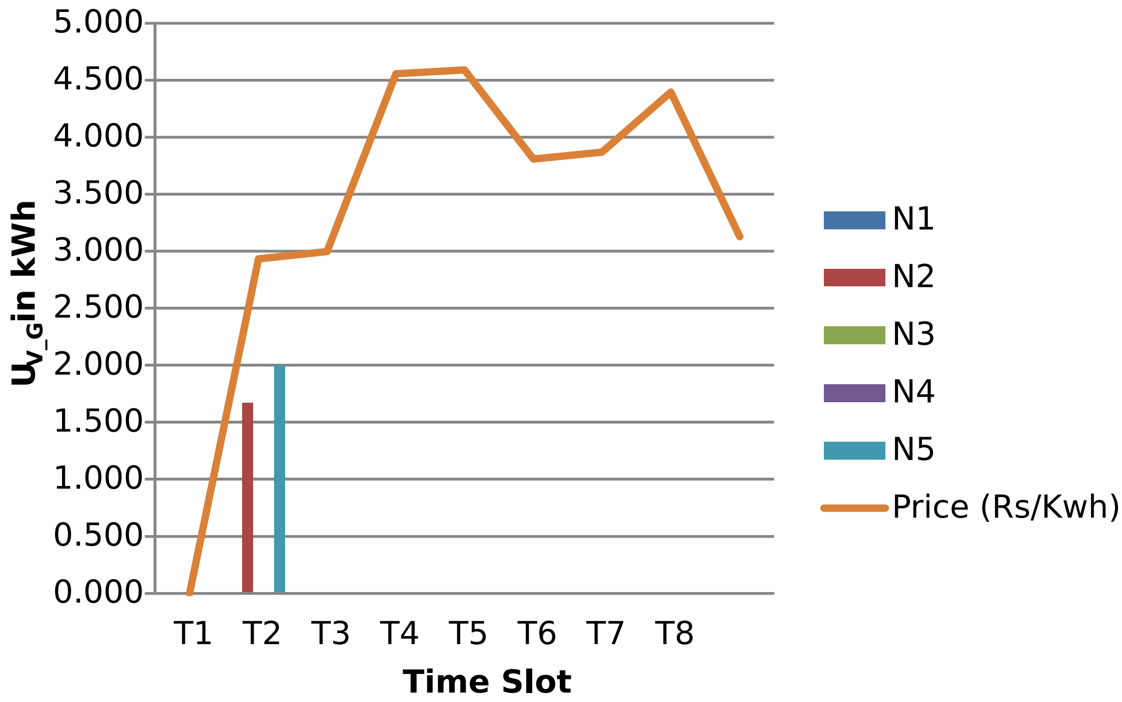

Figure 7.4: U_{V_G} for Identical PEVs charging With Priority

Table 7.2: b_{ij} for Identical PEVs charging With Priority

	N1	N2	N3	N4	N5
T1	-	-	-	-	-
T2	1	0	1	1	-
T3	-	1	1	1	-
T4	-	-	1	1	-
T5	-	-	-	-	-
T6	-	-	-	-	-
T7	-	-	-	-	-
T8	1	-	1	-	1

7. μ_{ij} : Systems' priority changes with duration of parking and charging and discharging of battery .For case 1A, it is calculated as shown in Table.7.3

Table 7.3: μ_{ij} for Identical PEVs charging With Priority

	N1	N2	N3	N4	N5
T1	0.750	0.625	0.500	0.500	0.750
T2	0.875	8.250	0.625	2.790	8.375
T3	-	0.875	0.750	0.750	-
T4	-	-	0.875	0.875	-
T5	-	-	-	-	-
T6	-	-	-	-	-
T7	-	-	-	-	-
T8	0.625	-	0.375	-	0.625

Charging happens without priority among PEVs(Case 1B)

1. **Objective**: The objective function value is found to be :-0.257
2. **Cost**: Charging cost is found to be :Rs -20.56 (Negative sign signifies that profit is realized)
3. U$_{G_Vij}$:The Energy consumed from Grid to vehicle for different vehicles and for different time slot can be shown through Fig.7.5.

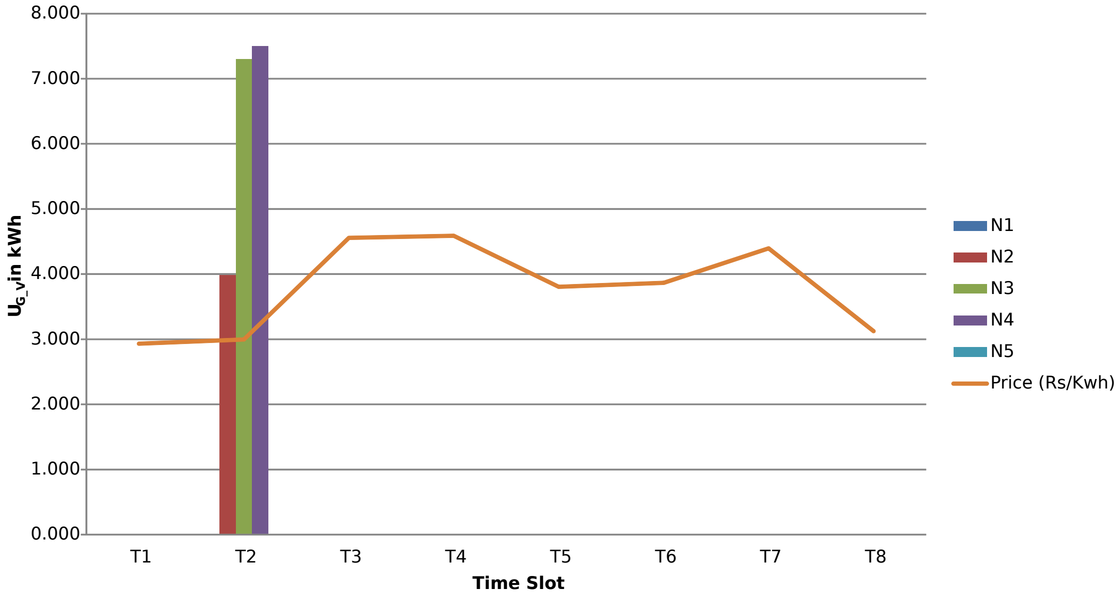

Figure 7.5: U_{G_V} for Identical PEVs charging Without Priority

4. U$_{V_Gij}$:The Energy consumed from vehicle to grid for different vehicles and for different time slot can be shown through Fig. 7.6

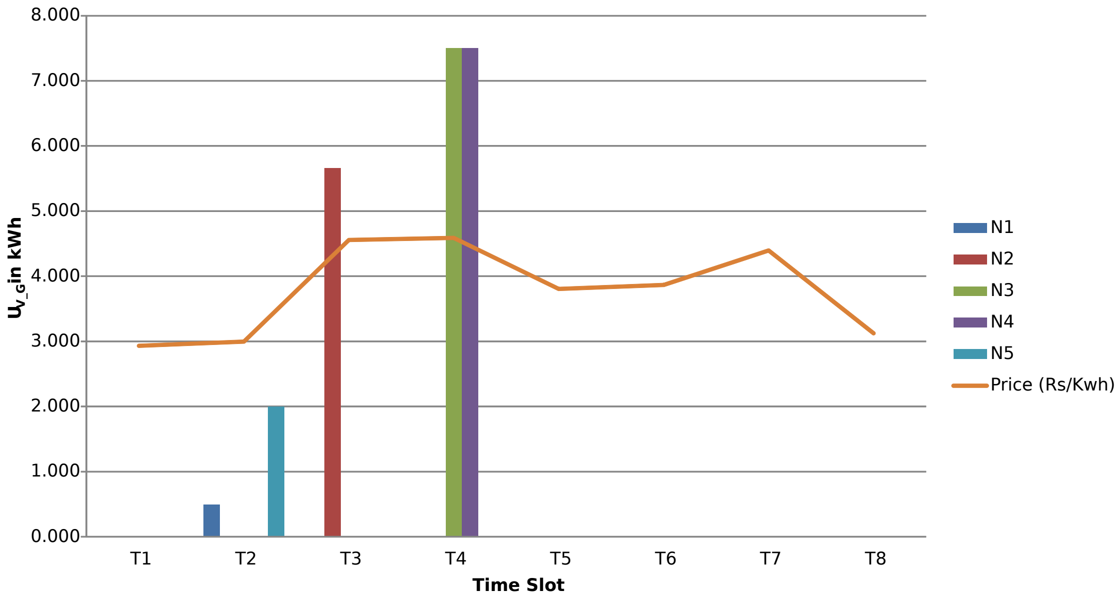

Figure 7.6: U_{V_G} for Identical PEVs charging Without Priority

5. **BE**$_{ij}$:The battery energy level of each PEV for case 1B, for full schedule can be shown in the form of Table.7.4.It is worth noting that when the PEV is not present the BE level is represented as the BE level of previous slot.

Table 7.4: BE$_{ij}$ levels for Identical PEVs charging Without Priority

	N1	N2	N3	N4	N5
T1	6.500	7.670	6.200	6.000	8.000
T2	6.000	11.659	13.500	13.500	6.000
T3	6.000	6.000	13.500	13.500	6.000
T4	6.000	6.000	6.000	6.000	6.000
T5	6.000	6.000	6.000	6.000	6.000
T6	6.000	6.000	6.000	6.000	6.000
T7	6.000	6.000	6.000	6.000	6.000
T8	6.000	6.000	6.000	6.000	6.000

6. **b**$_{ij}$: The variable b is binary, it is 1 when G2V operation takes place and when it is 0 then V2G operation can take place.Table.7.5 shows the value of b for case 1B.

Table 7.5: b$_{ij}$ for Identical PEVs charging Without Priority

	N1	N2	N3	N4	N5
T1	-	-	-	-	-
T2	-	1	1	1	0
T3	-	0	1	1	-
T4	-	-	0	0	-
T5	-	-	-	-	-
T6	-	-	-	-	-
T7	-	-	-	-	-
T8	1	-	1	-	1

7. μ_{ij} : Systems' priority changes with duration of parking and charging and discharging of battery .For case 1B, it is calculated as shown in Table.7.6

Table 7.6: μ_{ij} for Identical PEVs charging Without Priority

	N1	N2	N3	N4	N5
T1	0.750	0.625	0.500	0.500	0.750
T2	8.375	2.591	0.625	0.625	8.375
T3	-	8.375	0.750	0.750	-
T4	-	-	8.375	8.375	-
T5	-	-	-	-	-
T6	-	-	-	-	-
T7	-	-	-	-	-
T8	8.125	-	7.875	-	8.125

Priority Premium Calculation

As defined in Chapter 6, we will use the cost of charging obtained for presence matrix of different events described in Chapter 5, to come up with estimate of charging cost and use that to determine Priority premium to be levied upon Users'.The calculation can be tabulated as in Table.7.7.It is to be noted that negative sign signifies that profit is realized.

Table 7.7: Cost of Charging for different Events for Identical PEVs

Event	Probability(p)	Cost With priority(Rs)	Cost Without Priority(Rs)	Difference(D)	$D * p$
P1	0.468	139.28	-20.56	159.84	74.834
P2	0.026	139.28	-21.12	160.40	4.172
P3	0.041	126.64	-17.44	144.08	5.952
P4	0.026	139.28	-20.32	159.60	4.151
P5	0.059	139.28	-20.32	159.60	9.340
P6	0.041	150.88	-22.72	173.60	7.171
P7	0.026	135.44	-21.04	156.48	4.070
P8	0.041	139.28	-20.72	160.00	6.610
P9	0.026	139.28	-20.56	159.84	4.157
P10	0.059	139.28	-20.56	159.84	9.354
P11	0.041	147.84	-22.4	170.24	7.033
Total Probability	0.855			Total D*p	136.845

From Table5.6, Total Weight = 15.So,

$$Premiumperunitweight = TotalD * p \div (TotalProbability * TotalWeight) \quad (7.1)$$

Using Eq.7.1, premium per unit =10.68 Rs

So For each PEV,the priority premium can be given as in Table. 7.8

Table 7.8: Priority Premium for Each PEV for Identical PEVs charging Without Priority

PEV	Weight	Premium for One Day(Rs)	One Year Premium(Rs)
N1	5	53	19484
N2	2	21	7794
N3	4	43	15587
N4	3	32	11691
N5	1	11	3897

7.1.2 Results for Identical PEVs with Different Charging Rate

In this case, each PEV is of the same capacity, but their charging rates are different

Charging happens with priority among PEVs

1. **Objective**: The objective function value is found to be :154.116

2. **Cost**: Charging cost is found to be :Rs 135.92

3. **U**$_{G\_Vij}$:The Energy consumed from Grid to vehicle for different vehicles and for different time slot can be shown through Fig.7.7

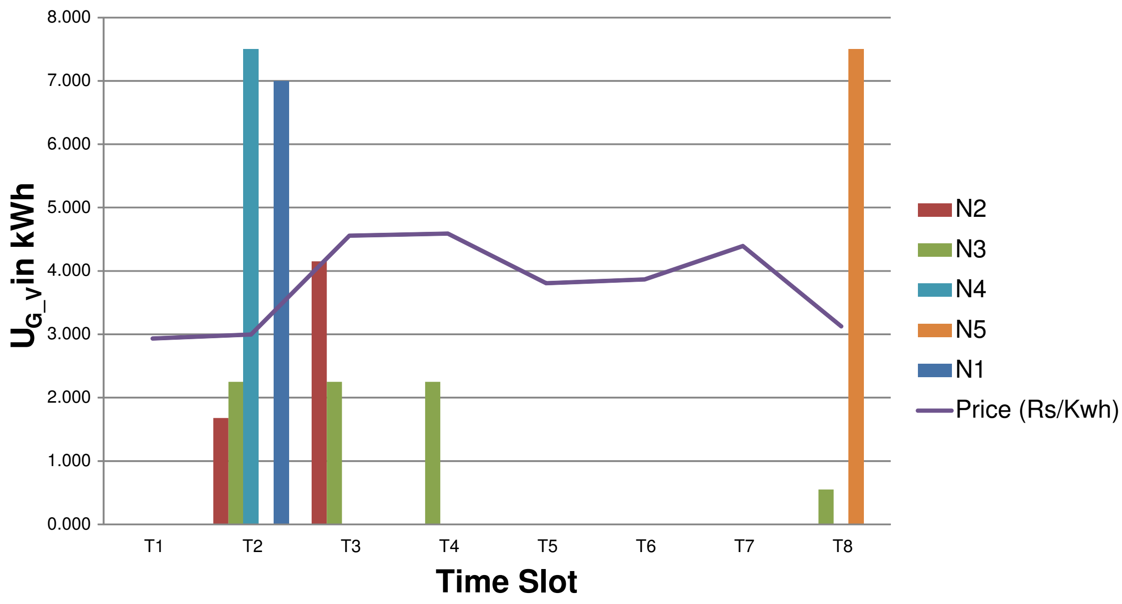

Figure 7.7: U_{G_V} for Differently charging PEVs with priority

4. **U**$_{V\_Gij}$:The Energy consumed from vehicle to grid for different vehicles and for different time slot can be shown through Fig. 7.8

5. **BE**$_{ij}$:The battery energy level of each PEV for case 2A, for full schedule can be shown in the form of Table.7.9.It is worth noting that when the PEV is not present then BE level is represented as the BE level of previous slot.

6. **b**$_{ij}$: The variable b is binary, it is 1 when G2V operation takes place and when it is 0 then V2G operation can take place.Table.7.10 shows the value of b for case 2A.

7. μ_{ij} : Systems' priority changes with duration of parking and charging and discharging of battery .For case 2A, it is calculated as shown in Table.7.11

Charging happens without priority among PEVs

1. **Objective**: The objective function value is found to be :-0.233

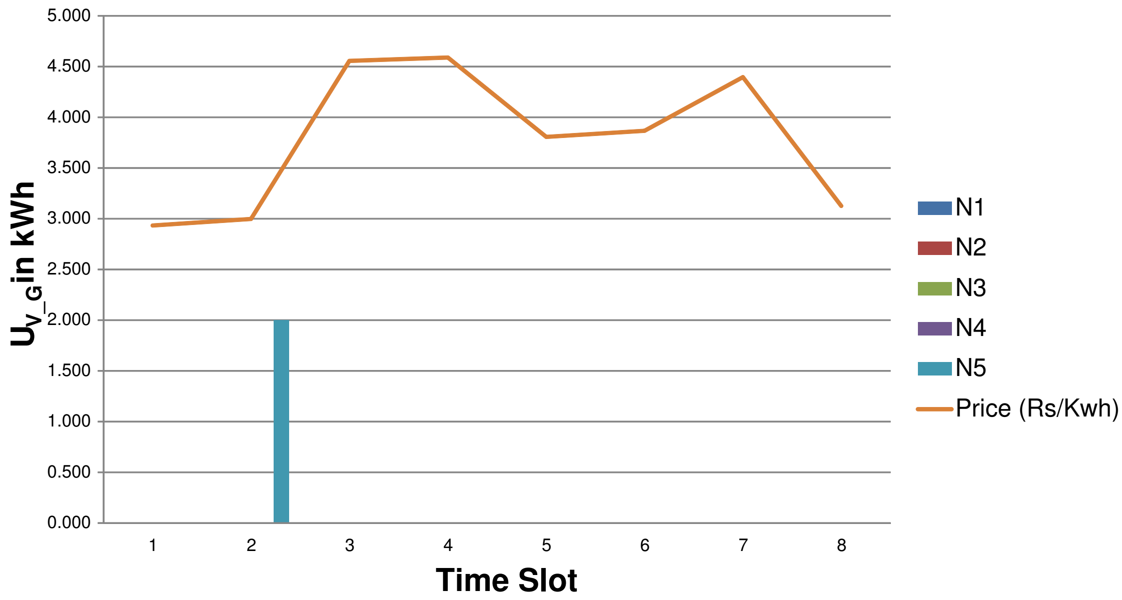

Figure 7.8: U_{V_G} for Differently charging PEVs with priority

Table 7.9: BE_{ij} levels for Differently charging PEVs with priority

	N1	N2	N3	N4	N5
T1	6.50	7.67	6.20	6.00	8.00
T2	13.500	9.348	8.450	13.500	6.000
T3	13.500	13.500	10.700	13.500	6.000
T4	13.500	13.500	12.950	13.500	6.000
T5	13.500	13.500	12.950	13.500	6.000
T6	13.500	13.500	12.950	13.500	6.000
T7	13.500	13.500	12.950	13.500	6.000
T8	13.50	13.50	13.50	13.50	13.50

Table 7.10: b_{ij} for Differently charging PEVs with priority

	N1	N2	N3	N4	N5
T1	-	-	-	-	-
T2	1	1	1	1	0
T3	-	1	1	1	-
T4	-	-	1	1	-
T5	-	-	-	-	-
T6	-	-	-	-	-
T7	-	-	-	-	-
T8	1	-	1	-	1

2. **Cost**: Charging cost is found to be :Rs -18.64 (Negative sign signifies that profit is realized)

3. **U**$_{G\_Vij}$:The Energy consumed from Grid to vehicle for different vehicles and for different time slot can be shown through Fig.7.9

4. **U**$_{V\_Gij}$:The Energy consumed from vehicle to grid for different vehicles and for different time slot can be shown through Fig. 7.10

Table 7.11: μ_{ij} for Differently charging PEVs with priority

	N1	N2	N3	N4	N5
T1	1.750	1.625	1.500	1.500	1.750
T2	1.875	5.902	6.675	1.625	9.375
T3	-	1.875	4.550	1.750	-
T4	-	-	2.425	1.875	-
T5	-	-	-	-	-
T6	-	-	-	-	-
T7	-	-	-	-	-
T8	1.625	-	1.375	-	1.625

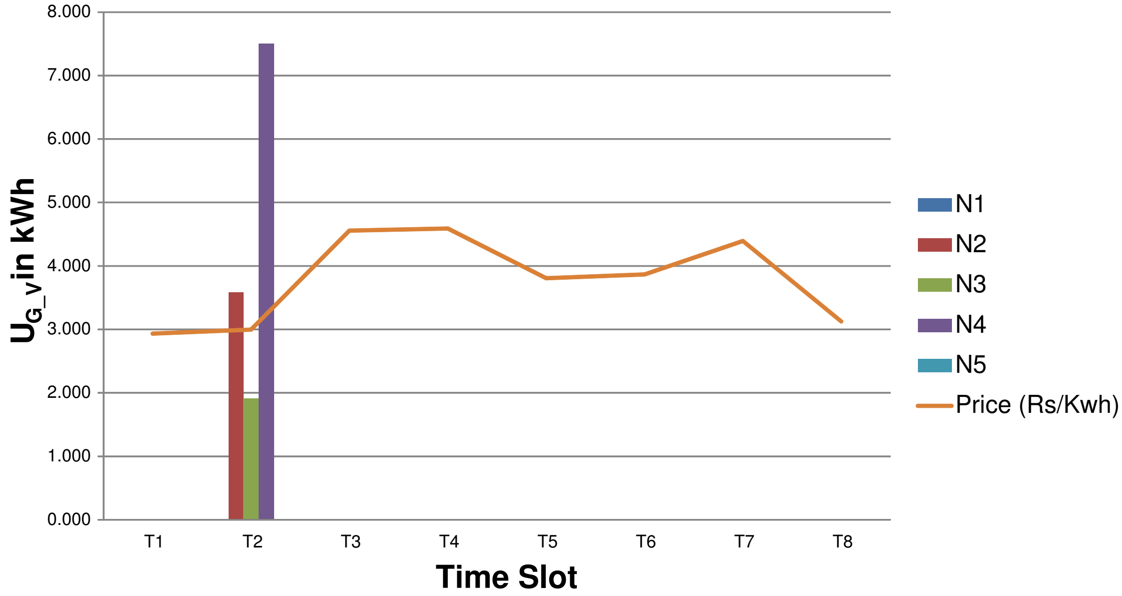

Figure 7.9: U_{G_V} for Differently charging PEVs without priority

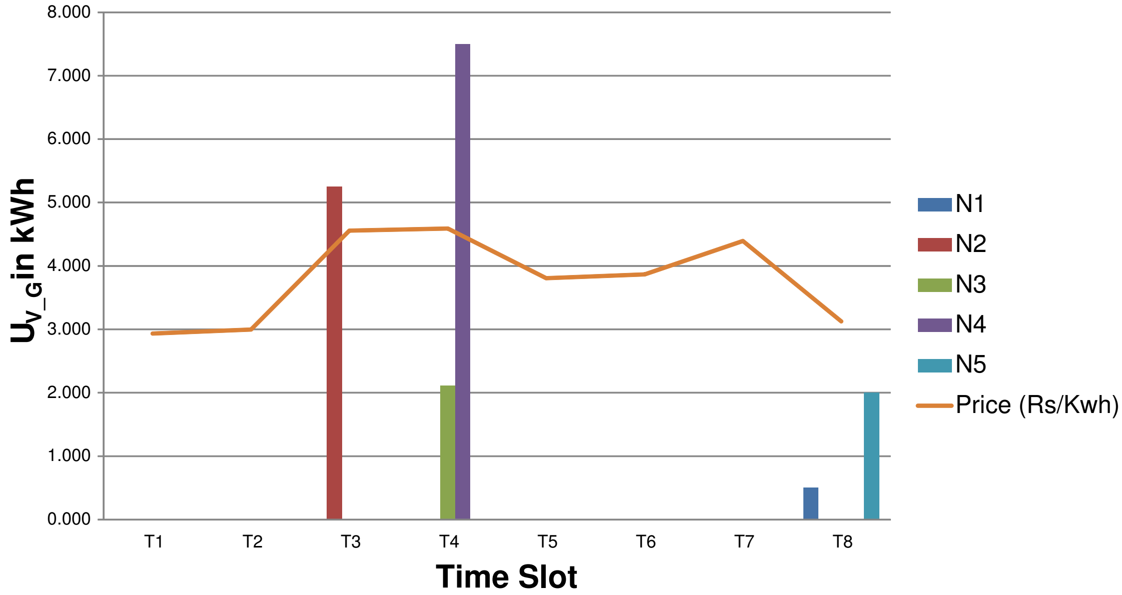

Figure 7.10: U_{V_G} for Differently charging PEVs without priority

5. **BE**$_{ij}$:The battery energy level of each PEV for case 2B, for full schedule can be shown in the form of Table.7.12.It is worth noting that when the PEV is not

present then BE level is represented as the BE level of previous slot.

Table 7.12: BE_{ij} levels for Differently charging PEVs without priority

	N1	N2	N3	N4	N5
T1	6.500	7.670	6.200	6.000	8.000
T2	6.500	11.250	8.113	13.500	8.000
T3	6.500	6.000	8.113	13.500	6.000
T4	6.500	6.000	6.000	6.000	8.000
T5	6.500	6.000	6.000	6.000	8.000
T6	6.500	6.000	6.000	6.000	8.000
T7	6.500	6.000	6.000	6.000	8.000
T8	6.000	6.000	6.000	6.000	6.000

6. $\mathbf{b}_{ij}$: The variable b is binary, it is 1 when G2V operation takes place and when it is 0 then V2G operation can take place.Table.7.13 shows the value of b for case 2B.

Table 7.13: b_{ij} for Differently charging PEVs without priority

	N1	N2	N3	N4	N5
T1	-	-	-	-	-
T2	1	1	1	1	1
T3	-	0	1	1	-
T4	-	-	0	0	-
T5	-	-	-	-	-
T6	-	-	-	-	-
T7	-	-	-	-	-
T8	0	-	1	-	0

7. μ_{ij} : Systems' priority changes with duration of parking and charging and discharging of battery .For case 2B, it is calculated as shown in Table.7.14

Table 7.14: μ_{ij} for Differently charging PEVs without priority

	N1	N2	N3	N4	N5
T1	1.750	1.625	1.500	1.500	1.750
T2	8.875	4.000	7.012	1.625	7.375
T3	-	9.375	7.137	1.750	-
T4	-	-	9.375	9.375	-
T5	-	-	-	-	-
T6	-	-	-	-	-
T7	-	-	-	-	-
T8	9.125	-	8.875	-	9.125

Priority Premium Calculation

As defined in Chapter 6, we will use the cost of charging obtained for presence matrix of different events described in Chapter 5, to come up with estimate of charging cost and use that to determine Priority premium to be levied upon Users'.The calculation can be tabulated as in Table.7.15.It is to be noted that negative sign signifies that profit is realized

Table 7.15: Cost of Charging for different Events for Differently charging PEVs

Event	Probability(p)	Cost With priority(Rs)	Cost Without Priority(Rs)	Difference(D)	$D * p$
P1	0.468	135.92	-18.64	154.56	72.362
P2	0.026	135.92	-20.96	156.88	4.080
P3	0.041	128.96	-15.52	144.48	5.968
P4	0.026	135.44	-18.72	154.16	4.010
P5	0.059	135.92	-18.56	154.48	9.041
P6	0.041	148.56	-22.56	171.12	7.069
P7	0.026	138.32	-19.36	157.68	4.101
P8	0.041	135.92	-19.52	155.44	6.421
P9	0.026	136.4	-18.8	155.2	4.037
P10	0.059	135.92	-18.8	154.72	9.055
P11	0.041	144.56	-20.96	165.52	6.838
Total Probability	0.855			Total *D*p*	132.982

From Table5.6, Total Weight = 15.

Using Eq.7.1, premium per unit =Rs 10.37 ,so for each PEV,the priority premium can be given as in Table 7.16

Table 7.16: Priority Premium for Each PEV for Differently charging PEVs

PEV	Weight	Premium for One Day(Rs)	One Year Premium(Rs)
N1	5	52	18934
N2	2	21	7574
N3	4	41	15147
N4	3	31	11361
N5	1	10	3787

7.1.3 Results for charging different PEVs

This is the general case in which both capacity as well as charging rate of the PEVs are different.

Charging happens with priority among PEVs

1. **Objective**: The objective function value is found to be :338.355
2. **Cost**: Charging cost is found to be :Rs -239.68 (Negative sign signifies that profit is realized)
3. **U**$_{G\_Vij}$:The Energy consumed from Grid to vehicle for different vehicles and for different time slot can be shown through Fig.7.11

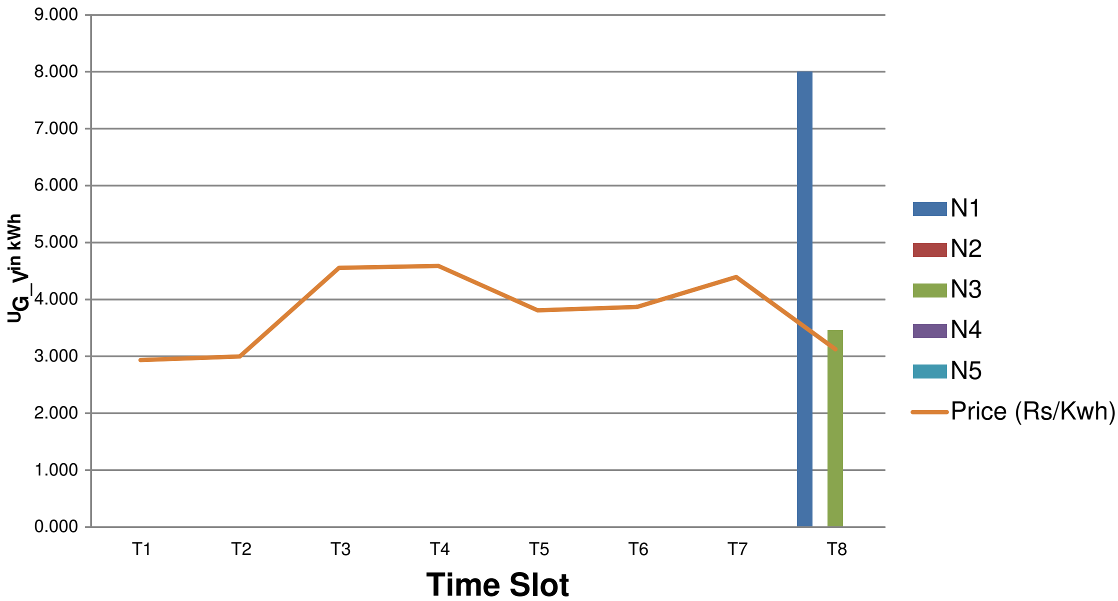

Figure 7.11: U_{G_V} for charging different PEVs with Priority

4. **U**$_{V\_Gij}$:The Energy consumed from vehicle to grid for different vehicles and for different time slot can be shown through Fig. 7.12
5. **BE**$_{ij}$:The battery energy level of each PEV for case 3A, for full schedule can be shown in the form of Table.7.17.It is worth noting that when the PEV is not present then BE level is represented as the BE level of previous slot.
6. **b**$_{ij}$: The variable b is binary, it is 1 when G2V operation takes place and when it is 0 then V2G operation can take place.Table.7.18 shows the value of b for case 3A.
7. μ_{ij} : Systems' priority changes with duration of parking and charging and discharging of battery .For case 3A, it is calculated as shown in Table.7.19

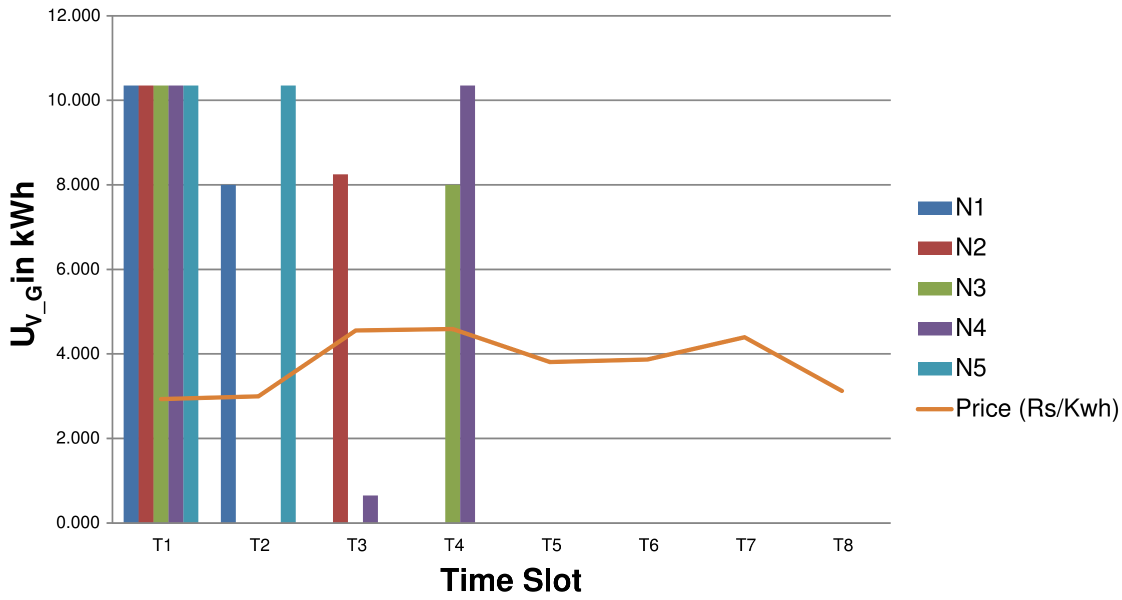

Figure 7.12: U_{V_G} for charging different PEVs with Priority

Table 7.17: BE$_{ij}$ levels for charging different PEVs with Priority

	N1	N2	N3	N4	N5
T1	16.000	16.500	16.000	22.000	45.350
T2	8.000	16.500	16.000	22.000	35.000
T3	8.000	8.250	16.000	21.350	35.000
T4	8.000	8.250	8.000	11.000	35.000
T5	8.000	8.250	8.000	11.000	35.000
T6	8.000	8.250	8.000	11.000	35.000
T7	8.000	8.250	8.000	11.000	35.000
T8	16.000	8.250	11.458	11.000	35.000

Table 7.18: b$_{ij}$ for charging different PEVs with Priority

	N1	N2	N3	N4	N5
T1	-	-	-	-	-
T2	-	1	1	1	0
T3	-	0	1	0	-
T4	-	-	0	0	-
T5	-	-	-	-	-
T6	-	-	-	-	-
T7	-	-	-	-	-
T8	1	-	1	-	1

Charging happens without priority among PEVs

1. **Objective**: The objective function value is found to be :-3.523
2. **Cost**: Charging cost is found to be :Rs -281.84 (Negative sign signifies that profit is realized)
3. **U**$_{G\_Vij}$:The Energy consumed from Grid to vehicle for different vehicles and for different time slot can be shown through Fig.7.13

Table 7.19: μ_{ij} for charging different PEVs with Priority

	N1	N2	N3	N4	N5
T1	1.750	1.625	1.500	1.500	26.400
T2	9.875	1.750	1.625	1.625	36.875
T3	-	10.125	1.750	2.400	-
T4	-	-	9.875	12.875	-
T5	-	-	-	-	-
T6	-	-	-	-	-
T7	-	-	-	-	-
T8	1.625	-	5.917	-	36.625

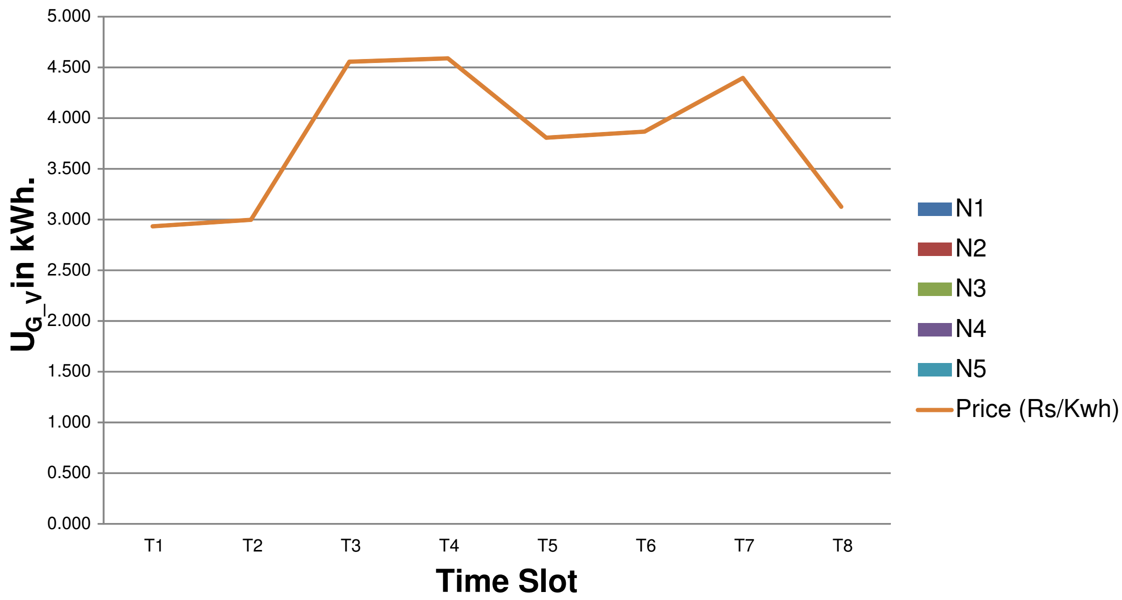

Figure 7.13: U_{G_V} for charging different PEVs without Priority

4. U$_{V_Gij}$:The Energy consumed from vehicle to grid for different vehicles and for different time slot can be shown through Fig. 7.14

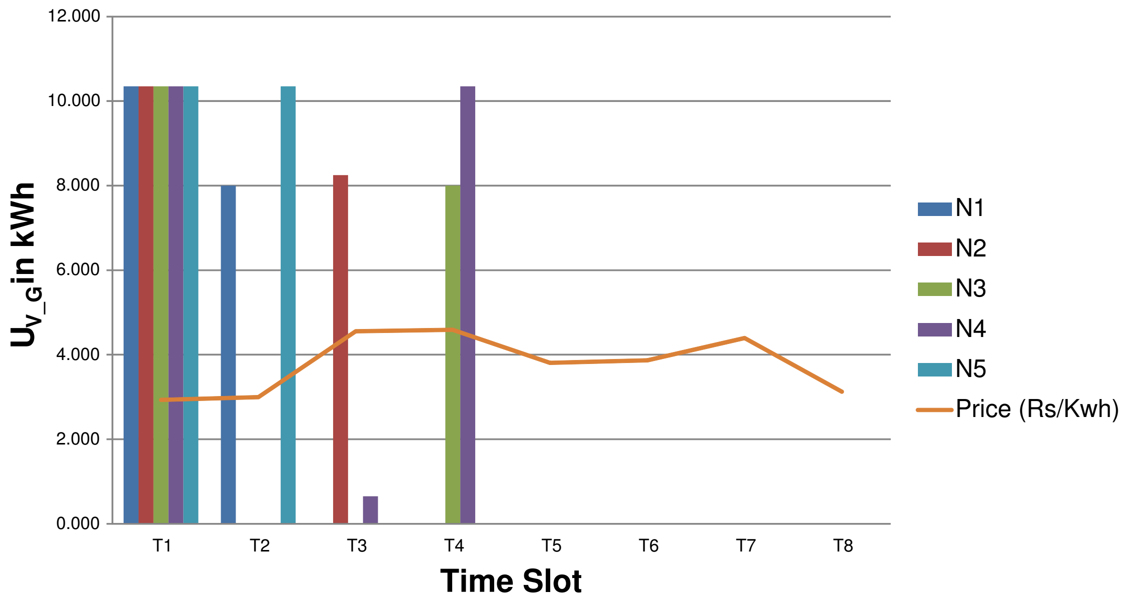

Figure 7.14: U_{V_G} for charging different PEVs without Priority

5. **BE**$_{ij}$:The battery energy level of each PEV for case 3B, for full schedule can be shown in the form of Table 7.20.It is worth noting that when the PEV is not present then BE level is represented as the BE level of previous slot.

Table 7.20: BE$_{ij}$ levels for charging different PEVs without Priority

	N1	N2	N3	N4	N5
T1	16.000	16.500	16.000	22.000	45.350
T2	8.000	16.500	16.000	22.000	35.000
T3	8.000	8.250	16.000	21.350	35.000
T4	8.000	8.250	8.000	11.000	35.000
T5	8.000	8.250	8.000	11.000	35.000
T6	8.000	8.250	8.000	11.000	35.000
T7	8.000	8.250	8.000	11.000	35.000
T8	8.000	8.250	8.000	11.000	35.000

6. **b**$_{ij}$: The variable b is binary, it is 1 when G2V operation takes place and when it is 0 then V2G operation can take place.Table.7.21 shows the value of b for case 3B.

Table 7.21: b$_{ij}$ for charging different PEVs without Priority

	N1	N2	N3	N4	N5
T1	-	-	-	-	-
T2	-	1	1	1	0
T3	-	0	1	0	-
T4	-	-	0	0	-
T5	-	-	-	-	-
T6	-	-	-	-	-
T7	-	-	-	-	-
T8	0	-	0	-	1

7. μ_{ij} : Systems' priority changes with duration of parking and charging and discharging of battery .For case 3B, it is calculated as shown in Table.7.22

Table 7.22: μ_{ij} for charging different PEVs without Priority

	N1	N2	N3	N4	N5
T1	1.750	1.625	1.500	1.500	26.400
T2	9.875	1.750	1.625	1.625	36.875
T3	-	10.125	1.750	2.400	-
T4	-	-	9.875	12.875	-
T5	-	-	-	-	-
T6	-	-	-	-	-
T7	-	-	-	-	-
T8	9.625	-	9.375	-	36.625

Priority Premium Calculation

As defined in Chapter6, we will use the cost of charging obtained for presence matrix of different events described in Chapter 5, to come up with estimate of charging cost and use that to determine Priority premium to be levied upon Users'.The calculation can be tabulated as in Table.7.23.It is to be noted that negative sign signifies that profit is realized

Table 7.23: Cost of Charging for different Events for charging different PEVs

Event	Probability(p)	Cost With priority(Rs)	Cost Without Priority(Rs)	Difference(D)	$D * p$
P1	0.47	-239.68	-281.84	42.16	19.74
P2	0.03	-250.32	-292.4	42.08	1.09
P3	0.04	-228.72	-270.88	42.16	1.74
P4	0.03	-198.08	-281.6	83.52	2.17
P5	0.06	-238.56	-280.64	42.08	2.46
P6	0.04	-279.76	-321.92	42.16	1.74
P7	0.03	-177.92	-261.44	83.52	2.17
P8	0.04	-185.04	-227.12	42.08	1.74
P9	0.03	-234.4	-281.84	47.44	1.23
P10	0.06	-164.16	-216.4	52.24	3.06
P11	0.04	-167.84	-255.44	87.60	3.62
Total Probability	0.855			Total *D*p*	40.77

From Table5.6, Total Weight = 15.

Using Eq.7.1, premium per unit =Rs 3.18 ,so for each PEV,the priority premium can be given as in Table 7.24

Table 7.24: Priority Premium for Each PEV for Charging different PEVs without Priority

PEV	Weight	Premium for One Day(Rs)	One Year Premium(Rs)
N1	5	16	5805
N2	2	6	2322
N3	4	13	4644
N4	3	10	3483
N5	1	3	1161

We can consolidate the priority premium for all scenarios in a table(Table7.25) for understanding the pattern among them

Table 7.25: Cost of charging in different cases and priority premium for each PEV

			Weights	5	2	4	3	1
			PEV	N1	N2	N3	N4	N5
Scenario	Priority	Profit (Rs)	Diff	Premium (Rs)	Premium (Rs)	Premium (Rs)	Premium (Rs)	Premium (Rs)
Identical PEV	With	-139.52						
Identical PEV	Without	20.56	160.08	53.38	21.35	42.71	32.03	10.68
Charging Rate Different	With	-136.72						
Charging Rate Different	Without	18.96	155.68	51.87	20.75	41.50	31.12	10.37
Different PEV	With	226.72						
Different PEV	Without	274.48	47.76	15.90	6.36	12.72	9.54	3.18

7.2 Observations & Inference

7.2.1 Observations

Through the value of different variables, as presented in section7.1 we can draw following observations :

1. All the solutions obtained are global optima because of NLP to MILP conversion
2. Charging is scheduled intelligently, such that the G2V operation takes place when cost of electricity is less, and vice versa for V2G operation.
3. In **Case iB**, at the end of charging schedule BE always goes to minimum value possible, whereas in **Case iA**, charging is scheduled so that BE touches BE_{max}
4. G2V operation takes place more frequently when there is priority among PEVs, as is evident from analysis of Fig.(7.3,7.7,7.11) vs Fig.(7.5,7.9,7.13)
5. In case of Scenario 3, G2V operation takes place vary rarely.It can be seen as in Fig.7.11, where only in last Time slot (T8), G2V operation is taking place, & also in Fig.7.13, where no G2V operation takes place at all.Also BE levels in case 3A do not go to maximum, as was the case in other two scenarios.
6. **Case iB** is always more profitable than **case iA** which shows that there is a cost of lost opportunity associated whenever PEV demands priority on the basis of duration(d_{ij}) ,Battery energy(BE_{ij}) and weight(W_j). This cost is levied upon the PEVs in the form of premium.

7. From presence matrix given in Table.5.2, we observe that PEV N1 is available for shorter duration and has high Weight, therefore in all test cases it is given high priority and it is charged first as is evident in column 1 of table 7.1.

8. PEV N3 & PEV N4 are available almost for the same time but Weight for N3 is greater than Weight of N4, and therefore higher overall priority goes to N3 and it charges before N4, to its maximum capacity (Table7.1)

9. Cost of premium is divided proportionately according to weights of each PEV

10. When compared Premium for PEV in Scenario 1 and Scenario 2, it is observed that price decreases slightly.

7.2.2 Inference

On the basis of observations made in section.7.2.1, following inferences can be drawn :

1. Distribution companies set the price of electricity in such a way that during lean period ,the price of electricity is less, so by intelligent scheduling, charging operation is shifted to lean period time in order to save money and hence it helps in preventing overloading of the system.Also,V2G process scheduled in charging schedule, allows aggregator to use PEV as Power source in case of high demand (High Price) period, and thus allow to make profit.

2. Case iB, represents charging without priority, and hence in absence of any additional constraint from user i.e., priority, charging scheduling is optimized to make most profit, and therefore more V2G operations are scheduled , as well as BE levels goes to minimum at the end of charging schedule.On the other hand ,when priority is included, as in Case iA, system becomes more rigid ,and preference is given to accumulate energy to reduce priority of PEV, so frequency of G2V operations are increased and BE level goes to maximum at the end of charging schedule.

3. In scenario 3, as the Battery capacity of all PEVs are significantly larger than the charging power P_{max}, so BE levels do not go to maximum in case 3A.Also,G2V operation is rare.This dictates the need for faster charging options at the parking stations ,to get maximum benefit of V2G & G2V operation and use of PEV as energy source.

4. Due to less V2G operation in Case iA, charging cost is increased, as compared to case iB where always , the user is making profit (in all scenarios discussed) by the help of V2G operation.

5. When we introduced different charging rates, the premium prices are reduced, which shows that charging costs are reduced and system is able to find charging schedule which will incur less cost.This can be attributed to the fact that by introducing different charging rates,we are introducing more flexibility in the system.Same is true ,if we compare costs of Scenario 3 ,with others.

6. Premium Cost is levied proportionate to the Users' priority instead of equally charging everyone, as there is loss of opportunity cost, whenever a user gives more preference to charge their PEV, and hence the scheduling is not optimized fully,so this method penalizes users' for assigning more priority to their PEV as compared to others.This in turn provides a monetary benefit to Aggregator as well as other Users' to compensate the loss of opportunity cost.

Summary

In this chapter result obtained after solving the optimization problem for different cases and events are noted and they are used to draw different conclusion and inferences regarding the effect of priority are studied.These results are used to calculate the premium for each PEV in different cases and their variations is also studied.

CHAPTER 8

CONCLUSION & FUTURE SCOPE

8.1 Conclusion

A novel method for premium determination and charging scheduling is proposed. The reformulation is imposed to convert Non-Linear Programming (NLP) problem to Mixed-Integer Linear Programming (MILP) problem.This helps us to get global optimal solution of all the cases. Intelligent charging schedule helps in avoiding overloading of the distribution system and provide extra source of energy during high demand periods. It is seen that, assuming priority charging schedule causes an extra financial burden on aggregator which is levied proportionally on the PEV customers. The intelligent charging scheduling and the premium levied upon the EV users allows the aggregator to make profits and reimburse the cost of lost opportunity when giving priority charging.

8.2 Future Scope

This work can be further expanded to include the cases where the number of EV become variable or follows a distribution.Also, there are numerous techniques which don't require distribution of random variable for estimation.Those methods can be applied in conjunction with proposed strategy.This will help to utilize the solution for commercial parking station and commercial charging stations as well.

Effect of charging -discharging cycle on the health of Batteries can be taken into account, as in real world, health and life estimation of battery are also important to ascertain profitability of EVs and estimate the lost opportunity cost

APPENDIX A

Remaining Presence & Duration matrices

A.1 Remaining Presence Matrices

Other presence matrices except for P1 are given as follows:

Table A.1: Presence Matrix P2 for event(s=2)

	N1	N2	N3	N4	N5
T1	1	1	1	1	1
T2	1	1	1	1	1
T3	1	1	1	1	0
T4	0	0	1	1	0
T5	0	0	0	0	0
T6	0	0	0	0	0
T7	0	0	0	0	0
T8	0	0	1	0	1

Table A.2: Presence Matrix P3 for event(s=3)

	N1	N2	N3	N4	N5
T1	1	1	1	1	1
T2	1	1	1	1	1
T3	0	0	1	1	0
T4	0	0	1	1	0
T5	0	0	0	0	0
T6	0	0	0	0	0
T7	0	0	0	0	0
T8	1	1	1	0	1

Table A.3: Presence Matrix P4 for event(s=4)

	N1	N2	N3	N4	N5
T1	1	1	1	1	1
T2	1	1	1	1	1
T3	0	1	1	1	0
T4	0	0	0	1	0
T5	0	0	0	0	0
T6	0	0	0	0	0
T7	0	0	1	0	0
T8	1	0	1	0	1

Table A.4: Presence Matrix P5 for event(s=5)

	N1	N2	N3	N4	N5
T1	1	1	1	1	1
T2	1	1	1	1	1
T3	0	1	1	1	0
T4	0	0	1	0	0
T5	0	0	0	0	0
T6	0	0	0	0	0
T7	0	0	0	0	0
T8	1	0	1	1	1

Table A.5: Presence Matrix P6 for event(s=6)

	N1	N2	N3	N4	N5
T1	1	1	1	1	1
T2	1	1	1	1	1
T3	0	1	1	1	1
T4	0	0	1	1	0
T5	0	0	0	0	0
T6	0	0	0	0	0
T7	0	0	0	0	0
T8	1	0	1	0	0

Table A.6: Presence Matrix P7 for event(s=7)

	N1	N2	N3	N4	N5
T1	1	1	1	1	1
T2	0	1	1	1	1
T3	0	1	1	1	0
T4	0	0	1	1	0
T5	0	0	0	0	0
T6	0	0	0	0	0
T7	1	0	0	0	0
T8	1	0	1	0	1

Table A.7: Presence Matrix P8 for event(s=8)

	N1	N2	N3	N4	N5
T1	1	0	1	1	1
T2	1	1	1	1	1
T3	0	1	1	1	0
T4	0	1	1	1	0
T5	0	0	0	0	0
T6	0	0	0	0	0
T7	0	0	0	0	0
T8	1	0	1	0	1

Table A.8: Presence Matrix P9 for event(s=9)

	N1	N2	N3	N4	N5
T1	1	1	1	1	1
T2	1	1	1	1	1
T3	0	1	1	1	0
T4	0	0	1	1	0
T5	0	0	1	0	0
T6	0	0	0	0	0
T7	0	0	0	0	0
T8	1	0	0	0	1

Table A.9: Presence Matrix P10 for event(s=10)

	N1	N2	N3	N4	N5
T1	1	1	1	0	1
T2	1	1	1	1	1
T3	0	1	1	1	0
T4	0	0	1	1	0
T5	0	0	0	1	0
T6	0	0	0	0	0
T7	0	0	0	0	0
T8	1	0	1	0	1

Table A.10: Presence Matrix P11 for event(s=11)

	N1	N2	N3	N4	N5
T1	1	1	1	1	1
T2	1	1	1	1	0
T3	0	1	1	1	0
T4	0	0	1	1	0
T5	0	0	0	0	0
T6	0	0	0	0	0
T7	0	0	0	0	1
T8	1	0	1	0	1

A.2 Remaining Duration Matrices

Remaining Duration matrices to be formed depending on TableA.1-Table.A.10, can be given as follows:

Table A.11: Duration Matrix for P2

	N1	N2	N3	N4	N5
T1	3	3	4	4	2
T2	2	2	3	3	1
T3	1	1	2	2	0
T4	0	0	1	1	0
T5	0	0	0	0	0
T6	0	0	0	0	0
T7	0	0	0	0	0
T8	0	0	5	0	3

Table A.12: Duration Matrix for P3

	N1	N2	N3	N4	N5
T1	2	2	4	4	2
T2	1	1	3	3	1
T3	0	0	2	2	0
T4	0	0	1	1	0
T5	0	0	0	0	0
T6	0	0	0	0	0
T7	0	0	0	0	0
T8	3	3	5	0	3

Table A.13: Duration Matrix for P4

	N1	N2	N3	N4	N5
T1	2	3	3	4	2
T2	1	2	2	3	1
T3	0	1	1	2	0
T4	0	0	0	1	0
T5	0	0	0	0	0
T6	0	0	0	0	0
T7	0	0	5	0	0
T8	3	0	4	0	3

Table A.14: Duration Matrix for P5

	N1	N2	N3	N4	N5
T1	2	3	4	3	2
T2	1	2	3	2	1
T3	0	1	2	1	0
T4	0	0	1	0	0
T5	0	0	0	0	0
T6	0	0	0	0	0
T7	0	0	0	0	0
T8	3	0	5	4	3

Table A.15: Duration Matrix for P6

	N1	N2	N3	N4	N5
T1	2	3	4	4	3
T2	1	2	3	3	2
T3	0	1	2	2	1
T4	0	0	1	1	0
T5	0	0	0	0	0
T6	0	0	0	0	0
T7	0	0	0	0	0
T8	3	0	5	0	0

Table A.16: Duration Matrix for P7

	N1	N2	N3	N4	N5
T1	1	3	4	4	2
T2	0	2	3	3	1
T3	0	1	2	2	0
T4	0	0	1	1	0
T5	0	0	0	0	0
T6	0	0	0	0	0
T7	3	0	0	0	0
T8	2	0	5	0	3

Table A.17: Duration Matrix for P8

	N1	N2	N3	N4	N5
T1	2	0	4	4	2
T2	1	3	3	3	1
T3	0	2	2	2	0
T4	0	1	1	1	0
T5	0	0	0	0	0
T6	0	0	0	0	0
T7	0	0	0	0	0
T8	3	0	5	0	3

Table A.18: Duration Matrix for P9

	N1	N2	N3	N4	N5
T1	2	3	5	4	2
T2	1	2	4	3	1
T3	0	1	3	2	0
T4	0	0	2	1	0
T5	0	0	1	0	0
T6	0	0	0	0	0
T7	0	0	0	0	0
T8	3	0	0	0	3

Table A.19: Duration Matrix for P10

	N1	N2	N3	N4	N5
T1	2	3	4	0	2
T2	1	2	3	4	1
T3	0	1	2	3	0
T4	0	0	1	2	0
T5	0	0	0	1	0
T6	0	0	0	0	0
T7	0	0	0	0	0
T8	3	0	5	0	3

Table A.20: Duration Matrix for P11

	N1	N2	N3	N4	N5
T1	2	3	4	4	1
T2	1	2	3	3	0
T3	0	1	2	2	0
T4	0	0	1	1	0
T5	0	0	0	0	0
T6	0	0	0	0	0
T7	0	0	0	0	3
T8	3	0	5	0	2

APPENDIX B

GAMS CODE

B.1 For Identical PEVs

B.1.1 Charging with priority

The GAMS Code used to solve case for different Events can be given as :

```
$onEolCom
sets
         i Time slots /T1*T8/
         j No.of cars /N1*N5/;

scalar
         car_number /5/ !! number of cars
         eta efficiency for vehicle to grid energy transfer
                                                      /0.85/
         pmax max charging power of battery charger in Kw
                                                       /5/
         T total number of time slots /8/
         M a very large number for nlp to mip conversion
                                                   /10000/
         max_load maximum load allowed in Kw /20/ ;

Table P(i,j) Availability Matrix
          N1       N2       N3       N4       N5
T1         1        1        1        1        1
T2         1        1        1        1        1
T3         0        1        1        1        0
T4         0        0        1        1        0
```

```
T5          0          0          0          0          0
T6          0          0          0          0          0
T7          0          0          0          0          0
T8          1          0          1          0          1;

Table d(i,j) Duration slot matrix

            N1         N2         N3         N4         N5
T1          2          3          4          4          2
T2          1          2          3          3          1
T3          0          1          2          2          0
T4          0          0          1          1          0
T5          0          0          0          0          0
T6          0          0          0          0          0
T7          0          0          0          0          0
T8          3          0          5          0          3;
parameters

         pi(i) rate of electricity
                 /T1 0.03667
                 T2 0.03746
                 T3 0.05695
                 T4 0.05736
                 T5 0.04758
                 T6 0.04834
                 T7 0.05494
                 T8 0.03908/;

Positive Variables
         Ug_v(i,j) energy transferred from grid to vehicle
         Uv_g(i,j) energy transferred from vehicle to grid
         BE(i,j) Battery energy stored  ;
         Ug_v.up(i,j)=P(i,j)*pmax*(24/T);
```

```
        Uv_g.up(i,j)=P(i,j)*pmax*(24/T);
        BE.up(i,j)=13.5                ;
        BE.lo(i,j)=6                   ;
Binary Variable b(i,j);

variables
        objective objective function variable
        cost cost of charging
        mu(i,j) priority variable;

equations
        obj objective function
        cost_equation
        charging_station_constraint(i,j) constraint
        on maximum charging power
        next_slot_energy(i,j) next time slot energy
         co1
         co2
        priority_calculation(i,j) calculate the priority
        max_load_constraint(i) constraint over maxload;
table weight(j,*)
     w
N1   5
N2   2
N3   4.5
N4   3
N5   1;

obj .. objective =e=sum((i,j),((Ug_v(i,j)/eta-eta*Uv_g(i,j))
          *P(i,j))*pi(i))+ sum((i,j),mu(i,j)*weight(j,'w'));
cost_equation .. cost=e=sum((i,j),((Ug_v(i,j)/eta-eta*
                                  Uv_g(i,j))*P(i,j))*pi(i));
charging_station_constraint(i,j) ..Ug_v(i,j)/eta-eta
```

```
                                    *Uv_g(i,j)=l= pmax*24/T;
next_slot_energy(i,j)$(ord(i)>1) .. BE(i,j)=e= BE(i-1,j)+
                                 (Ug_v(i,j)) - (Uv_g(i,j)) ;
co1(i,j) .. Ug_v(i,j) =l= M*(b(i,j))*P(i,j);   !!constraints
                                     to convert nlp into mip
co2(i,j) .. Uv_g(i,j) =l= M*(1-b(i,j))*P(i,j);
priority_calculation(i,j)..mu(i,j)=e=P(i,j)*((BE.up(i,j)+1)
                                      - (d(i,j)/T)-BE(i,j));
max_load_constraint(i) .. sum(j,(Ug_v(i,j)/eta-eta*Uv_g(i,j)))
                                        =l=max_load - 0.02;

Model vehicle /all/;
BE.fx('T1','N4')=6;
BE.fx('T1','N1')=6.5;
BE.fx('T1','N2')=7.67;
BE.fx('T1','N3')=6.2;
BE.fx('T1','N5')=8;
Ug_v.fx('T1',j)=0;
Uv_g.fx('T1',j)=0;
solve vehicle using mip minimizing objective;
```

B.1.2 Charging without priority

The GAMS Code used to solve case for different Events can be given as :

```
$onEolCom
sets
     i Time slots /T1*T8/
     j No.of cars /N1*N5/;

scalar
         car_number /5/ !! number of cars
         eta efficiency for vehicle to grid energy transfer
                                                      /0.85/
```

```
        pmax max charging power of battery charger in
                                                   Kw /5/
        T total number of time slots /8/
        M a very large number for nlp to mip conversion
                                                  /10000/
        max_load maximum load allowed in Kw /20/ ;

Table P(i,j) Availability Matrix
          N1       N2       N3       N4       N5
T1        1        1        1        1        1
T2        1        1        1        1        1
T3        0        1        1        1        0
T4        0        0        1        1        0
T5        0        0        0        0        0
T6        0        0        0        0        0
T7        0        0        0        0        0
T8        1        0        1        0        1;

Table d(i,j) Duration slot matrix

          N1       N2       N3       N4       N5
T1        2        3        4        4        2
T2        1        2        3        3        1
T3        0        1        2        2        0
T4        0        0        1        1        0
T5        0        0        0        0        0
T6        0        0        0        0        0
T7        0        0        0        0        0
T8        3        0        5        0        3;
parameters

        pi(i) rate of electricity in EUR per
        KWh from nordic pool as on 14th march 2018
```

```
        for each time slot
                /T1 0.03667
                T2 0.03746
                T3 0.05695
                T4 0.05736
                T5 0.04758
                T6 0.04834
                T7 0.05494
                T8 0.03908/;

Positive Variables
        Ug_v(i,j) energy transferred from grid to vehicle
        Uv_g(i,j) energy transferred from vehicle to grid
        BE(i,j) Battery energy stored in each time slot
        for each vehicle      ;
        Ug_v.up(i,j)=P(i,j)*pmax*(24/T);
        Uv_g.up(i,j)=P(i,j)*pmax*(24/T);
        BE.up(i,j)=13.5                  ;
        BE.lo(i,j)=6                     ;
Binary Variable b(i,j);

variables
        objective objective function variable
        cost cost of charging
        mu(i,j) priority variable;

equations
        obj objective function
        cost_equation
        charging_station_constraint(i,j)
        next_slot_energy(i,j) next time slot energy
         co1  !!constraints to convert qcp into mip
         co2
```

```
         priority_calculation(i,j) calculate the priority
         max_load_constraint(i) constraint over maxload ;
table weight(j,*)
     w
N1   5
N2   2
N3   4
N4   3
N5   1;

obj .. objective =e=sum((i,j),((Ug_v(i,j)/eta-eta*Uv_g(i,j))*
                                                   P(i,j))*pi(i));
cost_equation .. cost=e=sum((i,j),((Ug_v(i,j)/eta-eta
                                         *Uv_g(i,j))*P(i,j))*pi(i));
charging_station_constraint(i,j) ..Ug_v(i,j)/eta-eta*Uv_g(i,j)
                                                     =l= pmax*24/T;
next_slot_energy(i,j)$(ord(i)>1) .. BE(i,j)=e= BE(i-1,j)
                                    + (Ug_v(i,j)) - (Uv_g(i,j)) ;
co1(i,j) .. Ug_v(i,j) =l= M*(b(i,j))*P(i,j);
co2(i,j) .. Uv_g(i,j) =l= M*(1-b(i,j))*P(i,j);
priority_calculation(i,j)..mu(i,j)=e=P(i,j)*((BE.up(i,j)+1)
                                             - (d(i,j)/T)-BE(i,j));
max_load_constraint(i) .. sum(j,(Ug_v(i,j)/eta-eta*Uv_g(i,j)))
                                                  =l=max_load - 0.02;

Model vehicle /all/;
BE.fx('T1','N4')=6;
BE.fx('T1','N1')=6.5;
BE.fx('T1','N2')=7.67;
BE.fx('T1','N3')=6.2;
BE.fx('T1','N5')=8;
Ug_v.fx('T1',j)=0;
Uv_g.fx('T1',j)=0;
```

```
solve vehicle using mip minimizing objective;
```

B.2 For Differently Charging PEVs

B.2.1 Charging with priority

The GAMS Code used to solve case for different Events can be given as :

```
$onEolCom
sets
        i Time slots /T1*T8/
        j No.of cars /N1*N5/;

scalar
        eta efficiency for v2g energy transfer /0.85/
        pmax max charging power of battery charger
                                           in Kw /5/
        T total number of time slots /8/
        M a very large number for nlp to mip
                                 conversion  /10000/
        max_load maximum load allowed in Kw /20/ ;

Table P(i,j) Availability Matrix
         N1       N2       N3       N4       N5
T1       1        1        1        1        1
T2       1        1        1        1        1
T3       0        1        1        1        0
T4       0        0        1        1        0
T5       0        0        0        0        0
T6       0        0        0        0        0
T7       0        0        0        0        0
T8       1        0        1        0        1;
```

```
Table d(i,j) Duration slot matrix

          N1        N2        N3        N4        N5
T1        2         3         4         4         2
T2        1         2         3         3         1
T3        0         1         2         2         0
T4        0         0         1         1         0
T5        0         0         0         0         0
T6        0         0         0         0         0
T7        0         0         0         0         0
T8        3         0         5         0         3;
parameters

         pi(i) rate of electricity
                 /T1 0.03667
                 T2 0.03746
                 T3 0.05695
                 T4 0.05736
                 T5 0.04758
                 T6 0.04834
                 T7 0.05494
                 T8 0.03908/;

table cr(j,*) !!charging rate
     r
N1   0.55
N2   0.35
N3   0.15
N4   0.95
N5   0.8;
Positive Variables
         Ug_v(i,j) energy transferred from grid to vehicle
         Uv_g(i,j) energy transferred from vehicle to grid
```

```
         BE(i,j) Battery energy stored for each vehicle;
         Ug_v.up(i,j)=P(i,j)*pmax*(24/T)*cr(j,'r');
         Uv_g.up(i,j)=P(i,j)*pmax*(24/T)*cr(j,'r');
         BE.up(i,j)=13.5                         ;
         BE.lo(i,j)=6                            ;
Binary Variable b(i,j);

variables
         objective objective function variable
         cost cost of charging
         mu(i,j) priority variable;

equations
         obj objective function
         cost_equation
         charging_station_constraint(i,j)
         next_slot_energy(i,j) next time slot energy estimation
          co1  !!constraints to convert qcp into mip
          co2
         priority_calculation(i,j) calculate the priority
         max_load_constraint(i) constraint over maxload ;
table weight(j,*)
     w
N1   5
N2   2
N3   4
N4   3
N5   1;


obj .. objective =e=sum((i,j),((Ug_v(i,j)/eta-eta*Uv_g(i,j))
            *P(i,j))*pi(i))+ sum((i,j),mu(i,j)*weight(j,'w'));
cost_equation .. cost=e=sum((i,j),((Ug_v(i,j)/eta-eta
```

```
                                        *Uv_g(i,j))*P(i,j))*pi(i));
charging_station_constraint(i,j) ..Ug_v(i,j)/eta-eta*Uv_g(i,j)
                                                   =l= pmax*24/T;
next_slot_energy(i,j)$(ord(i)>1) .. BE(i,j)=e= BE(i-1,j)+
                                        (Ug_v(i,j)) - (Uv_g(i,j)) ;
co1(i,j) .. Ug_v(i,j) =l= M*(b(i,j))*P(i,j);
co2(i,j) .. Uv_g(i,j) =l= M*(1-b(i,j))*P(i,j);
priority_calculation(i,j)..mu(i,j)=e=P(i,j)*((BE.up(i,j)+2)
                                             - (d(i,j)/T)-BE(i,j));
max_load_constraint(i) .. sum(j,(Ug_v(i,j)/eta-eta*Uv_g(i,j)))
                                               =l=max_load - 0.02;

Model vehicle /all/;
BE.fx('T1','N4')=6;
BE.fx('T1','N1')=6.5;
BE.fx('T1','N2')=7.67;
BE.fx('T1','N3')=6.2;
BE.fx('T1','N5')=8;
Ug_v.fx('T1',j)=0;
Uv_g.fx('T1',j)=0;
solve vehicle using mip minimizing objective;
```

B.2.2 Charging without priority

The GAMS Code used to solve case for different Events can be given as :

```
$onEolCom
sets
         i Time slots /T1*T8/
         j No.of cars /N1*N5/;

scalar
         eta efficiency for vehicle to grid energy transfer
                                                        /0.85/
```

```
          pmax max charging power of battery charger in
                                                         Kw /5/
          T total number of time slots /8/
          M a very large number for nlp to mip conversion
                                                       /10000/
          max_load maximum load allowed in Kw /20/ ;

Table P(i,j) Availability Matrix
          N1        N2        N3        N4        N5
T1        1         1         1         1         1
T2        1         1         1         1         1
T3        0         1         1         1         0
T4        0         0         1         1         0
T5        0         0         0         0         0
T6        0         0         0         0         0
T7        0         0         0         0         0
T8        1         0         1         0         1;

Table d(i,j) Duration slot matrix

          N1        N2        N3        N4        N5
T1        2         3         4         4         2
T2        1         2         3         3         1
T3        0         1         2         2         0
T4        0         0         1         1         0
T5        0         0         0         0         0
T6        0         0         0         0         0
T7        0         0         0         0         0
T8        3         0         5         0         3;
parameters

          pi(i) rate of electricity
                  /T1 0.03667
```

```
                T2 0.03746
                T3 0.05695
                T4 0.05736
                T5 0.04758
                T6 0.04834
                T7 0.05494
                T8 0.03908/;

table cr(j,*) !!charging rate
     r
N1   0.55
N2   0.35
N3   0.15
N4   0.95
N5   0.8;
Positive Variables
         Ug_v(i,j) energy transferred from grid to vehicle
         Uv_g(i,j) energy transferred from vehicle to grid
         BE(i,j) Battery energy stored           ;
         Ug_v.up(i,j)=P(i,j)*pmax*(24/T)*cr(j,'r');
         Uv_g.up(i,j)=P(i,j)*pmax*(24/T)*cr(j,'r');
         BE.up(i,j)=13.5                         ;
         BE.lo(i,j)=6                            ;
Binary Variable b(i,j);

variables
         objective objective function variable
         cost cost of charging
         mu(i,j) priority variable;

equations
         obj objective function
         cost_equation
```

```
          charging_station_constraint(i,j)
          next_slot_energy(i,j) next time slot energy
           co1  !!constraints to convert qcp into mip
           co2
          priority_calculation(i,j) calculate the priority
          max_load_constraint(i) constraint over maxload ;
table weight(j,*)
     w
N1   5
N2   2
N3   4
N4   3
N5   1;


obj .. objective =e=sum((i,j),((Ug_v(i,j)/eta-eta*Uv_g(i,j))
                                                  *P(i,j))*pi(i));
cost_equation .. cost=e=sum((i,j),((Ug_v(i,j)/eta-eta
                                       *Uv_g(i,j))*P(i,j))*pi(i));
charging_station_constraint(i,j) ..Ug_v(i,j)/eta-eta
                              *Uv_g(i,j)=l= pmax*24/T*cr(j,'r');
next_slot_energy(i,j)$(ord(i)>1) .. BE(i,j)=e= BE(i-1,j)+
                                       (Ug_v(i,j)) - (Uv_g(i,j)) ;
co1(i,j) .. Ug_v(i,j) =l= M*(b(i,j))*P(i,j);
co2(i,j) .. Uv_g(i,j) =l= M*(1-b(i,j))*P(i,j);
priority_calculation(i,j)..mu(i,j)=e=P(i,j)*((BE.up(i,j)+2)
                                            - (d(i,j)/T)-BE(i,j));
max_load_constraint(i) .. sum(j,(Ug_v(i,j)/eta-eta*Uv_g(i,j)))
                                                 =l=max_load - 0.02;


Model vehicle /all/;
BE.fx('T1','N4')=6;
BE.fx('T1','N1')=6.5;
```

```
BE.fx('T1','N2')=7.67;
BE.fx('T1','N3')=6.2;
BE.fx('T1','N5')=8;
Ug_v.fx('T1',j)=0;
Uv_g.fx('T1',j)=0;
solve vehicle using mip minimizing objective;
```

B.3 For Different PEVs

B.3.1 Charging with priority

The GAMS Code used to solve case for different Events can be given as :

```
    $onEolCom
sets
         i Time slots /T1*T8/
         j No.of cars /N1*N5/;

scalar
         eta efficiency for vehicle to grid energy transfer
                                                      /0.85/
         pmax max charging power of battery charger in
                                                  Kw /3.45/
         T total number of time slots /8/
         M a very large number for nlp to mip conversion
                                                    /10000/
         max_load maximum load allowed in Kw /13.5/ ;
         !!for 4 cars at 230vac and 15 amps it comes
         to 13.8 so taking less than that

Table P(i,j) Availability Matrix
          N1       N2       N3       N4       N5
T1        1        1        1        1        1
```

```
T2          1          1          1          1          1
T3          0          1          1          1          0
T4          0          0          1          1          0
T5          0          0          0          0          0
T6          0          0          0          0          0
T7          0          0          0          0          0
T8          1          0          1          0          1;

Table d(i,j) Duration slot matrix

            N1         N2         N3         N4         N5
T1          2          3          4          4          2
T2          1          2          3          3          1
T3          0          1          2          2          0
T4          0          0          1          1          0
T5          0          0          0          0          0
T6          0          0          0          0          0
T7          0          0          0          0          0
T8          3          0          5          0          3;
parameters

         pi(i) rate of electricity
                 /T1 0.03667
                 T2 0.03746
                 T3 0.05695
                 T4 0.05736
                 T5 0.04758
                 T6 0.04834
                 T7 0.05494
                 T8 0.03908/;
Positive Variables
         Ug_v(i,j) energy transferred from grid to vehicle
         Uv_g(i,j) energy transferred from vehicle to grid
```

```
         BE(i,j) Battery energy stored ;

table weight(j,*)
     w
N1   5
N2   2
N3   4
N4   3
N5   1;

table cr(j,*) !!charging rate
     r
N1   0.55
N2   0.35
N3   0.15
N4   0.95
N5   0.8;
table max(j,*)
     rr
N1   8   !!chevy
N2   8.25 !!smart foto
N3   8  !!mitubishi
N4   11  !!BMW
N5   35;!!Tesla assuming a reserve
                !!of 1/2 BE for all

BE.fx('T1','N4')=0;
BE.fx('T1','N1')=0;
BE.fx('T1','N2')=0;
BE.fx('T1','N3')=0;
BE.fx('T1','N5')=0;
Ug_v.fx('T1',j)=0;
Uv_g.fx('T1',j)=0;
```

```
Ug_v.up(i,j)=P(i,j)*pmax*(24/T);
         Uv_g.up(i,j)=P(i,j)*pmax*(24/T);
         BE.up(i,j)=P(i,j)*max(j,'rr');
         BE.lo(i,j)=0 ;


Binary Variable b(i,j);

variables
         objective objective function variable
         cost cost of charging
         mu(i,j) priority variable;

equations
         obj objective function
         cost_equation
         charging_station_constraint(i,j)
         next_slot_energy(i,j) next time slot energy estimation
          co1  !!constraints to convert qcp into mip
          co2
         co3
         priority_calculation(i,j) calculate the priority
         max_load_constraint(i) constraint over maxload ;



obj .. objective =e=sum((i,j),((Ug_v(i,j)/eta-eta*Uv_g(i,j))
          *P(i,j))*pi(i))+ sum((i,j),mu(i,j)*weight(j,'w'));
cost_equation .. cost =e=sum((i,j),((Ug_v(i,j)/eta-eta
                                 *Uv_g(i,j))*P(i,j))*pi(i));
charging_station_constraint(i,j) ..Ug_v(i,j)/eta-eta
                                    *Uv_g(i,j)=l= pmax*24/T;
```

```
next_slot_energy(i,j)$(ord(i)>1) .. BE(i,j)=e= BE(i-1,j)+
                                  (Ug_v(i,j)) - (Uv_g(i,j)) ;
co3(i,j).. Ug_v(i,j)*Uv_g(i,j)=e=0;
co1(i,j) .. Ug_v(i,j) =l= M*(b(i,j))*P(i,j);
co2(i,j) .. Uv_g(i,j) =l= M*(1-b(i,j))*P(i,j);
priority_calculation(i,j)..mu(i,j)=e=P(i,j)*((BE.up(i,j) +2)
                                       - (d(i,j)/T)-BE(i,j));
max_load_constraint(i) .. sum(j,(Ug_v(i,j)/eta-eta*Uv_g(i,j)))
                                          =l=max_load - 0.02;

Model vehicle /all-co3/;
solve vehicle using mip minimizing objective;
```

B.3.2 Charging without priority

The GAMS Code used to solve case for different Events can be given as :

```
$onEolCom
sets
         i Time slots /T1*T8/
         j No.of cars /N1*N5/;

scalar
         eta efficiency for vehicle to grid energy transfer
                                                      /0.85/
         pmax max charging power of battery charger in
                                                   Kw /3.45/
         T total number of time slots /8/
         M a very large number for nlp to mip conversion
                                                    /10000/
         max_load maximum load allowed in Kw /13.5/ ;

Table P(i,j) Availability Matrix
          N1       N2       N3       N4       N5
```

```
T1          1          1          1          1          1
T2          1          1          1          1          1
T3          0          1          1          1          0
T4          0          0          1          1          0
T5          0          0          0          0          0
T6          0          0          0          0          0
T7          0          0          0          0          0
T8          1          0          1          0          1
       ;

Table d(i,j) Duration slot matrix

            N1         N2         N3         N4         N5
T1          2          3          4          4          2
T2          1          2          3          3          1
T3          0          1          2          2          0
T4          0          0          1          1          0
T5          0          0          0          0          0
T6          0          0          0          0          0
T7          0          0          0          0          0
T8          3          0          5          0          3
      ;
parameters

         pi(i) rate of electricity
                /T1 0.03667
                T2 0.03746
                T3 0.05695
                T4 0.05736
                T5 0.04758
                T6 0.04834
                T7 0.05494
                T8 0.03908/;
```

```
Positive Variables
         Ug_v(i,j) energy transferred from grid to vehicle
         Uv_g(i,j) energy transferred from vehicle to grid
         BE(i,j) Battery energy stored ;

table weight(j,*)
     w
N1   5
N2   2
N3   4
N4   3
N5   1;

table cr(j,*) !!charging rate
     r
N1   0.55
N2   0.35
N3   0.15
N4   0.95
N5   0.8;
table max(j,*)
     rr
N1   8   !!chevy
N2   8.25 !!smart foto
N3   8  !!mitubishi
N4   11  !!BMW
N5   35;!!Tesla assuming a reserve of 1/2 BE for all

BE.fx('T1','N4')=0;
BE.fx('T1','N1')=0;
BE.fx('T1','N2')=0;
BE.fx('T1','N3')=0;
BE.fx('T1','N5')=0;
```

```
Ug_v.fx('T1',j)=0;
Uv_g.fx('T1',j)=0;

Ug_v.up(i,j)=P(i,j)*pmax*(24/T);
         Uv_g.up(i,j)=P(i,j)*pmax*(24/T);
         BE.up(i,j)=P(i,j)*max(j,'rr');
         BE.lo(i,j)=0                ;



Binary Variable b(i,j);

variables
         objective objective function variable
         cost cost of charging
         mu(i,j) priority variable;

equations
         obj objective function
         cost_equation
         charging_station_constraint(i,j)
         next_slot_energy(i,j) next time slot energy
          co1  !!constraints to convert qcp into mip
          co2
         co3
         priority_calculation(i,j) calculate the priority
         max_load_constraint(i) constraint over maxload ;



obj .. objective =e=sum((i,j),((Ug_v(i,j)/eta-eta*Uv_g(i,j))
                                                   *P(i,j))*pi(i));
cost_equation .. cost =e=sum((i,j),((Ug_v(i,j)/eta-eta
                                        *Uv_g(i,j))*P(i,j))*pi(i));
```

```
charging_station_constraint(i,j) ..Ug_v(i,j)/eta-eta
                                    *Uv_g(i,j)=l= pmax*24/T;
next_slot_energy(i,j)$(ord(i)>1) .. BE(i,j)=e= BE(i-1,j)+
                                (Ug_v(i,j)) - (Uv_g(i,j)) ;
co3(i,j).. Ug_v(i,j)*Uv_g(i,j)=e=0;
co1(i,j) .. Ug_v(i,j) =l= M*(b(i,j))*P(i,j);
co2(i,j) .. Uv_g(i,j) =l= M*(1-b(i,j))*P(i,j);
priority_calculation(i,j)..mu(i,j)=e=P(i,j)*((BE.up(i,j) +2)
                                      - (d(i,j)/T)-BE(i,j));
max_load_constraint(i) .. sum(j,(Ug_v(i,j)/eta-eta*Uv_g(i,j)))
                                         =l=max_load - 0.02;

Model vehicle /all-co3/;
solve vehicle using mip minimizing objective;
```

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LIST OF PAPERS BASED ON THESIS

1. Vinit Khemka, Pranjal Pragya Verma, Anoop. V. E, and K.Shanti Swarup, "Intelligent Charging of PEV with Priority Premium Determination for Users in Parking Station", Submitted to *20^{th} National Power System Conference(2018) (Under Review).*