OPTIMAL SCHEDULING OF ELECTRIC VEHICLES

A DISSERTATION
Submitted in partial fulfilment of the requirement for the award of degree of

Master of technology

In

Electrical Engineering
(With specialization in Power System Engineering)

by

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CANDIDATE’S DECLARATION

I hereby declare that the dissertation report entitled “**Optimal Scheduling of Electric Vehicles”**, submitted to the Department of Electrical Engineering, Indian Institute of Technology, Roorkee, India, in partial fulfilment of the requirements for the award of the degree of **Master of Technology in Electrical Engineering** with specialization in Power Systems is an authentic record of the work carried out by me during the period from May 2018 to May 2019 under the supervision of **Dr. Dheeraj Kumar Khatod,** Associate Professor, Department of Electrical Engineering, Indian Institute of Technology, Roorkee. The matter presented in this dissertation report has not been submitted by me for the award of any other degree of this institute or any other institute.

(BHAVNEET SINGH)

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CERTIFICATE

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ABSTRACT

The conditions of environment are degrading in many countries due to increase in greenhouse gases. The solution of such impacts is to reduce the usage of fossil fuels. The electrification of transport sector is the best way to reduce these emissions. But increase in number of plug in electric vehicle (PEV) arise many problems like scarcity of electricity, increase in power fluctuations when connected to the grid. To deal with such problems, optimal scheduling of electric vehicle is very essential.

Two strategies are implemented. First one is profit maximization for PEV user. In this scenario charging of PEV is done when price of electricity is low and discharging of available energy inside the battery during peak hours using Vehicle to grid (V2G) concept. A Particle Swarm Optimization (PSO) algorithm is developed to implement this strategy. This increase the profit for PEV user and also reduces the peak to valley difference of the load profile. A mathematical model is developed having objective of increase the revenue of PEV user by satisfying the essential constraints value. Charging of PEVs when base load is less and discharging of PEVs when base load is high, indirectly helps the grid to satisfy the extra load and thus make the load profile as flat as possible.

In Second Strategy, problems like power transmission safety of branches and power fluctuations are taken into account and solved by modifying PSO algorithm. By taking the hourly electricity price data, the charging/discharging profile of particular PEV is found out independently. And also number of PEVs taking part in charging and discharging at each hour in 24 hour period can be obtained. The PSO algorithm runs with random distribution of PEVs i.e. EVs coming with different arrival and departure time. The constraint value such as certain amount of departure state of charge (SOC), maximum power through a particular branch etc. needs to be satisfied. A mathematical model is developed in the second strategy which takes care of benefits of PEV user and also reduces the fluctuations in the load profile after integration of PEVS in the existing system.

The PSO algorithm in both strategies find out the optimality of results. In profit maximization strategy, PSO finds the optimal charging and discharging instants of time during single or multiple transactions with the grid on a single day. In power optimization strategy, PSO runs for finding optimal charging and discharging power of PEVs. Simulations results shows the comparison between the uncoordinated charging and coordinated charging after integration of PEVs. The result shows that power optimization strategy maintains balance between PEV user profit and stable operation of grid. Thus on aggregate this proposed algorithm not only tries to flat the load profile but also helps the EV owner to generate revenue leading to more and more individuals shift towards combustion less energy and thus helps to control the pollution.

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Introduction

1.1 Introduction

The present electric power grid is undergoing a major overhaul for the first time since its inception. These changes are aimed at not only improving its overall functionality but also positively impacting the lives of the millions of people who are in one way or another dependent on it [1]. The term coined to denote this mass collaborative effort is the smart grid.

Making the smart grid a reality will involve the improvement of the existing power related infrastructure, as well as the introduction of new technology to work in conjunction with the existing infrastructure. Flexible AC Transmission System (FACTS) devices, extensive use of sensors, phasor measurement units (PMUs) and Plug-in Hybrid Electric Vehicles (PHEVs) are just a few examples of the new technologies that will be introduced for the realization of the smart grid. It is widely believed that PEVs will be the most vital component to make the smart grid a reality.

PEVs possess a number of features that make them an attractive option to both the smart grid and the PEV users as well. The defining characteristic of PEVs that has placed them in the spotlight is the Vehicle to Grid (V2G) feature. PEVs need to charge and draw power from the grid when the State of Charge (SOC) of its battery reaches low levels. The V2G property of PEVs would also allow PEVs to deliver power back to the grid.

The PEV features that would be beneficial to the smart grid are:

1. Bidirectional power flow between PEV and the grid would help to meet power requirements during periods of peak load demand.

2. The bidirectional property can also be used in order to charge the PEVs when the grid is at off peak hours.

3. Aggregated loads of PEVs could serve as means of energy storage and help the grid by providing ancillary services.

4. The aggregate load also helps in improving power quality by providing reactive power when necessary.

Similarly, PEVs are beneficial to the users in the following ways:

1. They are a source of revenue for the user via the V2G feature.

2. PEVs have superior fuel efficiency as compared to regular vehicles. This would further reduce the vehicle related expenditure for the users.

1.2 The PEV technology

A plug-in electric vehicle uses electric energy from the battery as its primary energy source [2]. The use of battery in PEV reduces or even eliminates the need for any kind of fuel. The vehicles has batteries to supply the required energy and these will need to plug into recharge.

1.2.1 Advantages of PEV Technology

The PEV technology has been found suitable and is promoted in various countries for its positive ecological impacts and climatic change challenges. Adoption of PEV has the following benefits:

- **Energy security:** Electricity is derived from household resources, while sinking petroleum imports resulting into nation’s energy autonomy. PEVs can contribute effectively to a unbiased assortment of domestically produced electrical energy.
- **Cleaner Environment:** Being environment friendly PEVs are effective in reducing total GHG emissions. The continuing tendency of increased electricity generation from renewable sources promises remuneration of reduced emissions.
- **Beneficial for economy:** PEVs have positive impacts on the local and as well as on national economies by creating new job opportunities in countries manufacturing PEV. Use of PEVs eliminates the fuel cost that produces less expensive transportation. PEV charging stations can be located at businesses, retail stores, colleges, workplaces, parks and libraries.
- **Vehicle to grid:** Taking energy from the grid when required and selling back electrical energy to the grid provided a market scenario for the owner.
  Battery can be charged when prices are low while the same can be discharged when electricity prices rise, thereby making the profit.

1.2.2 Different Types of Electric Vehicles

1. **Hybrid electric vehicles (HEVs):** The HEV uses a tiny battery to complement an interior ignition engine, it is re-energized by gasoline engine and regenerative braking.
2. **Plug-in hybrid electric vehicles (PHEVs):** PHEVs are driven by both electric motor and the interior ignition engine. We can charge them directly from the grid and also they have large battery capacity.
3. **Extended range electric vehicles (EREVs):** In EREV an electric generator is powered by interior ignition engine which is then used to charge the battery of the system. Unlike HEVs and PHEVs, wheels of the EREVs are driven by electric motor. The interior ignition engine only charges the battery.
4. **Battery electric vehicles (BEVs):** It does possess any interior ignition engine. It is charged directly from the grid. These types of vehicles have larger size of the battery as compared to any other type of electric vehicle.

1.2.3 PEV systems

PEVs use only electricity to propel them rather than any other kind of fuel or ignition engine [3].Various parts of PEV system are given below:

1. **Electric Motors:** It transforms electrical energy which is stored in the battery to mechanical energy, hence it makes the vehicle move forward or backward by AC or DC motor.

2. **Electric Generators:** The generator is used to convert mechanical energy into electrical energy. These generators are driven by internal combustion engine in some electric vehicles.

3. **Inverters:** The inverter converts DC power stored in the battery into AC and powers the AC motor where AC motor is used to drive the vehicle.

4. **Chargers:** They are used to convert AC taken from the grid into DC power, which can be then stored in the batteries of electric vehicles. They consist of a control mechanism that optimizes the charging process that also extends the life of the battery.

5. **Battery packs:** Electrical energy is stored in the batteries pack which is then used to power a PEV using a motor. Different EV uses different types of battery packs- lead acid, NiMH, Li-ion out of which Li-ion battery pack is more common. Battery packs attribute heavily to the significant price difference between normal vehicles and PEVs.

1.3 Problem Statement

The fact that the PEV is actually a source of income for the user poses a rather unique problem. Overusing the battery for V2G transactions in order to earn high amounts of money is a definite possibility. But directly charging or discharging the battery without considering the load demand arises more problem of increase of load during peak hours which further causes problems of large variation in load profile curve i.e. increase the burden of EV load to the existing system. This necessitates the need to have charging /discharging strategies in place.

Balancing the power grid requirements and profit to owners side by side is the main objective of this report. The enthusiasm around the smart grid along with the popularity of PEVs may wane if these problems are not properly addressed. The independent system operator (ISO) would be responsible to make the decision on whether a V2G, G2V or no transaction takes place. In order to make these decisions, the ISO would not only have to take grid conditions at any given time into consideration but also the relevant PEV parameters.

Having multiple objectives increases the complexity as far as reaching a solution is concerned. Each objective will have its own set of constraints and decision variables. Based on this, the dimensionality of the problem will vary from situation to situation. A principal step in developing said strategies would be to devise certain rules that form the basis for certain charge schedules. Lack of any definitive policy could result in PEVs doing more harm than good.

Depending on the scenario it may not be possible to achieve all the objectives. However, trade-offs will need to be made between the objectives. Optimization of these objectives will be necessary for the benefit of the electric utilities and PEV users. Swarm intelligence techniques were used in this thesis because they have shown the fastest computational times among the optimization algorithms.

Main objective here is to maximize the profit for the electric vehicle owners. Battery Health degradation can be reduced by having controlled number of V2G and G2V Transactions. Here battery degradation profile have not studied because then we have to go into the chemistry related with the charging and discharging characteristics of battery. A minimum SOC must be there in the PEV battery and thus this minimum SOC has considered as a discharging limit below which it cannot discharge while going for V2G transactions

1.4 Organisation of thesis

Chapter 1 provides the brief overview of PEV technology. The benefits and essential need for shifting towards the electric vehicle, is actually summarized in this chapter. The detailed study of coordination of power grid with the fleet of electric vehicle, impact of V2G and G2V on the existing power sector and different optimization techniques requires for meeting these objectives is studied from different journals, articles, papers etc. has provided in chapter 2. Chapter 3 summarizes different smart charging strategies which will be beneficial for grid as well as provides profit to PEV user. Comparison of these charging strategies by encountering different parameters such as voltage drop of a particular area, cost, peak power etc. is shown in this study. Chapter 5 shows the implementation of PSO strategy for meeting objectives such as profit maximization and curb the congestion during peak hours. The benefits of single transaction and multiple transactions of fleet of PEV with grid are shown in this chapter. The power optimization strategy using PSO is shown in the chapter 5. The need of optimal charging and discharging power, mathematical model for implementation of this optimization and finally flowchart describing the step by step procedure for implementing this strategy is shown in this chapter. Chapter 6 provides the conclusion of the whole dissertation as well as discusses on directions of future work. And finally last but not the least Appendix A contains the full description of working and methodology of PSO technique.

Chapter 2

Literature Review

Hexeberg [1] has suggested three different charging methods which are dumb charging, profit maximization and power factor control scenario. In this, dumb charging is a reference for the other two strategies and profit maximization strategy directly benefits Electric Vehicle consumers via G2V and V2G transactions at optimal charging and discharging instants and also benefits the grid during high peak hours i.e. congestion hours and thus helps to make the load profile as flat as possible. Hutson et al. [2] has proposed an intelligent method for scheduling of available energy storage capacity from plugin hybrid electric vehicles (PHEV) and electric vehicles (EV). A scalable parking lot model is developed with different parameters assigned to fleets of vehicles. This paper describes the particle swarm optimisation technique's benefits for the random arrival and departure of particles. It proposes a scalable parking model by considering different constraints like arrival time, departure time, available SOC in the battery while reaching to a parking lot and battery charging and discharging efficiency etc., to maximize the profit of each PEV user depending upon the hourly price of the unit. Honarmand et al. [3] has proposed a smart management and scheduling model for large number of EVs parked in an urban parking lot. The proposed model considered practical constraints such as desired charging electricity price, remaining battery capacity, remaining charging time and age of the battery. The proposed model also take care of the SOC while departure such that EV owner have sufficient amount of battery available so that EV owner can reach back home.

Swendsen [4] has worked on different infrastructure and compare these infrastructure on the basis of various factors to find out the optimal architecture for electric vehicle presence in the area of Bornholm. Kempton and Tomić [5] focusses on the vehicle to grid power fundamentals. The observation mainly roam around hybrid, battery and fuel cell electric vehicles and focusses on the benefits of V2G in technical aspects such as spinning reserve, peak power reduction etc.

Eberhart and Kennedy [6] cover basics of genetic algorithm. Del Valle Y, et al. [7] cover brief overview of particle swarm optimisation technique, its Variants and Applications in Power Systems. PSO involves the releasing of a number of particles that search the given solution space for the global optimum value of the function. One of the factors that has led to widespread acceptance of PSO as the algorithm of choice for optimization is because the computational times remain low even though the dimensionality of the problem increases. This is due to the fact that, PSO is modelled using linear equations. The movement of each particle naturally evolves to an optimal or near-optimal solution. Kennedy and Eberhart [8] work on algorithm of Binary particle swarm optimisation and proves it better to use if someone wants to work on discrete intervals.

Khanesar, et al. [9] has worked on different controlling actions requires during optimisation via BPSO. Lopes JAP, et al.[10] study the impact of integration of electric vehicles in existing power system. Different simulations carry out gives a detailed analysis mainly in two areas: the technical operation of grid and benefits arise after EV integration. Zhang Q, et al. [11] demonstrate quantitatively the technological, economic and environmental impacts of different supply policy selections and demand assumptions on future electricity systems and studied penetration of renewable energy generation in a future electricity system. Zhenpo and Peng [12] has analysed the charging power of PEV charging station and worked on the ways to make charging more efficient and quick. Galus and Anderson [13] has studied the demand management of PEVs when connected to the grid and how the demand is varied throughout the day in order to make charging cost efficient.

K.J. Dyke [14] studied the impacts of integrating PEVs in power system and how the negative impacts can be eliminated. Tomić and Kempton [15] has worked on a case study using fleet of electric drive vehicles and shows the characteristics of V2G as it provides a significant revenue stream that would improve the economics of grid-connected electric-drive vehicles and also improve the stability of the electrical grid. Haiming Fu et al. [16] has suggested a mathematical model for finding optimal charging and discharging power in order to reduce the power fluctuations, peak to valley difference and thus beneficial for PEV user and power grid. The PEVs are going to charge more in off peak hours and discharges during peak hours. This charging/discharging behaviour significantly increases the stability of the branch thus distributed network as whole. Also the coordinated charging curve follows the load curve of branch in most of the time instants, so the objective of reduction of power fluctuation also met. The algorithm finds the optimal charging and discharging power at each hour throughout the day satisfying all constraints within permissible limits. Due to V2G system, the problem of shortage of electricity for satisfying the load actually vanishes and load curve gets smoother with this strategy. The load data of a particular branch is available on an hour basis. If data availability is half an hour basis, then the profile gets smoother. Baran and Wu [17] has provided a novel solution for load balancing and loss reduction. It provides a load data curve of particular area and branch limits for flow of power to prevent it from overloading.

Chapter 3

Smart Charging Strategies

3.1 Need for smart charging

The electrification of transport sector has got some challenges also, since charging of PEVs lead to increase in the demand and if no charging strategy is installed then there is a possibility that demand will increase when all the vehicles owners would plug in their PEVs at the same time when they come home from their last journey of the day [1] . This may even cause a worst scenario when there is already a peak in demand. Hence charging of PEVs will place a sufficient pressure on the grid both at medium and low voltage levels. To avoid this, three charging strategies under the distributed infrastructure are studied in this chapter out of which one has been taken as a reference.

3.2 Charging Strategies

The three different charging strategies are discussed here which are following:

1. Dumb charging scenario: In this, there is no parameter verification neither is any objective of the owner of vehicle, just directly plug-in and charge the PEVs at unity power factor. There is not any kind of smart strategy involved in this scenario and it serves as a reference for comparing other two charging strategies. The dumb charging sometimes can result into peak in demand when there is already a peak in the base demand.

2. Profit maximization scenario: This scenario entirely dependent on RMCP (regulation market clearing price).The strategy is developed in such a way such that PEVs gets charge up or G2V transactions happen when the Price of unit is low and similarly V2G transactions happen i.e. discharging of stored energy back to grid, when charges are high in order to make profit. Both charging and discharging take place at unity power factor. Since the price curve follows the demand curve i.e. prices are high when demand is high and prices are low during low demand, this strategy will reduce the peak to valley difference and thus makes the demand profile as smooth as possible by incorporating all parameters.

3. Power factor control scenario: In this strategy, if there is a violation of voltage at any demand node the power factor of the charging is reduced and V2G transactions is done by mean of reactive power to maintain the node voltage above a particular level. So both these strategies i.e. profit maximization and power factor control consists a system that instruct the chargers to perform G2V or V2G transactions maintaining the level of power factor depending upon the circumstances.

3.3 The PQ circle:

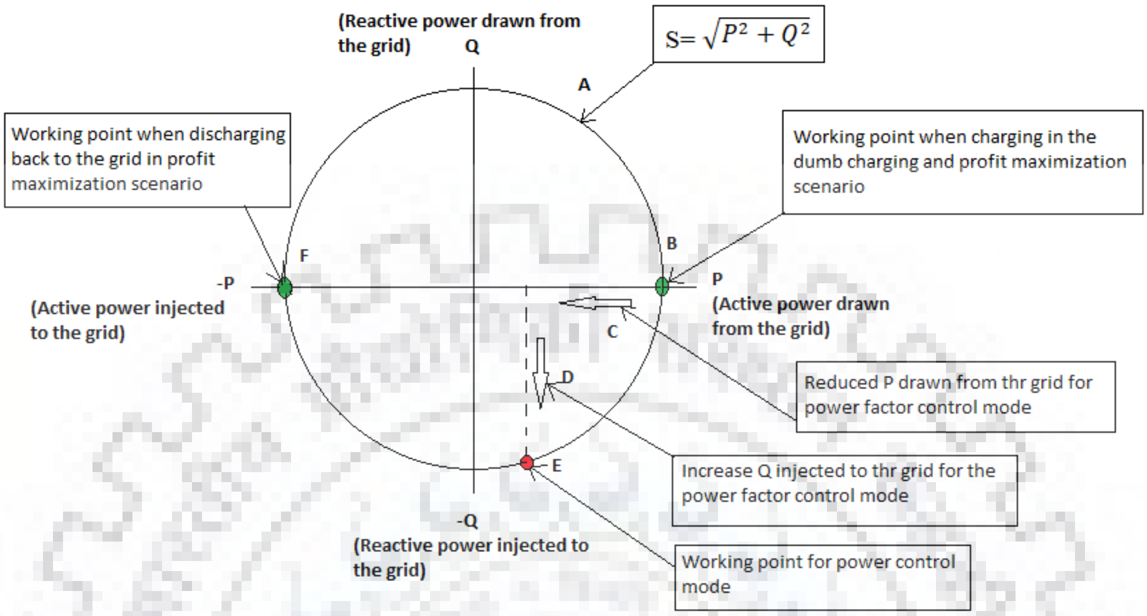


Fig 3.1: The PQ circle.

Fig 3.1 of PQ circle tells about the maximum apparent power that charger can allow to pass while charging/discharging. Mathematical relation shown as:

$$S = \sqrt{P^2 + Q^2}$$

This is given by point 'A' in the PQ circle. When maximum active power is taken from the grid the reactive power is taken to be zero, this is the case of dumb charging and profit maximization scenario and given by point 'B' of the PQ circle. In power factor control mode when voltage at some node is below the particular value the power factor of the charging is reduced by reducing the active power drawn from the grid, depicted by 'C' of the PQ circle, simultaneously reactive power is supplied back to the grid in order to increase the voltage at that node, this is given by point 'D' of the PQ circle. It has to be noted that when active power supply to the battery is reduced the charging time increases. Longer the time for charging, more the reactive power can be injected to the grid. 'E' represents the working point for the power factor control mode where less active power is supplied to the battery and sufficient amount of reactive power is supplied back to the grid. In case of profit maximization scenario, point 'F' represents the situation when power is given back to the grid in case of high electricity prices.

3.4 Case Study of different charging strategies

According to the national Danish travel survey the data for the parked vehicles in the Bornholm Island is taken into account [4].

1. Dumb charging scenario: It serves as a reference for other two charging strategies.

- **Demand pattern and voltage profile**: The dumb charging strategy will increase the daily peak demand by 46% between 18:00 and 21:00. This increase in demand due to the charging of PEVs also coincides with the peak of the base demand. From the figure it is clear that due to PEVs charging causes a high drop in the voltage level during peak hours i.e. when load is very high. The lowest level of voltage seen is 0.934 p.u in base load, but it reduces to 0.915 p.u. due to dumb charging strategy.

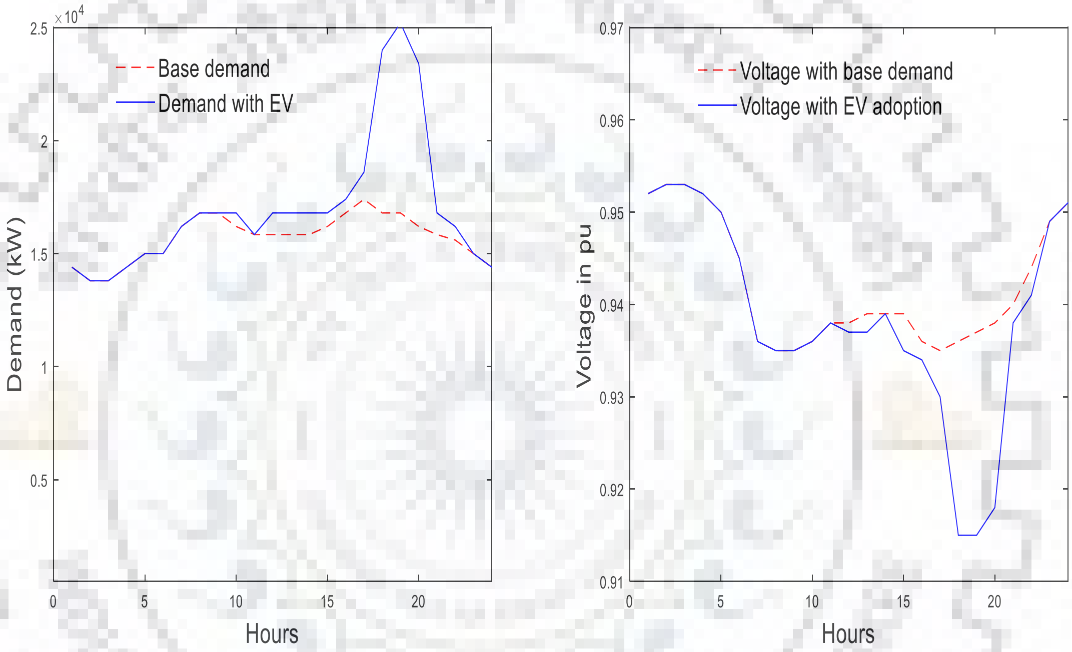


Fig 3.2: Demand and voltage comparison of dumb charging scenario.

2. Profit maximization scenario: The main objective of this scenario is to maximize the overall PEV fleet profit by charging at low prices and discharging back to the grid at high prices when required by the power system. This is the only scenario in which (V2G) transactions are there.

- **Demand pattern and voltage profile**: From Fig 3.3 it can be seen clearly that demand while charging the PEVs increases gradually from the evening when vehicles are plugged till the early morning. Also the base demand and original electricity price follow a similar pattern.During the hours from 16:00 to 19:00 the electricity pr ice reduces drastically as compared to the demand curve that only increases a bit and from 01:00 to 05:00 the electricity price reduces less as compared to the increase in demand.During the afternoon till evening the demand and electricity price with PEVs adoption reduces as profit maximization technique is supplying power back to the grid (V2G). From the figure, the peak in demand around 02:00 causes a dip in the voltage, the minimum voltage is reduced from 0.934 pu at 08:00 with only the base demand to 0.932 pu at 02:00 with the adoption of PEVs. This voltage difference after introducing the EV is less as compared to dumb charging scenario.

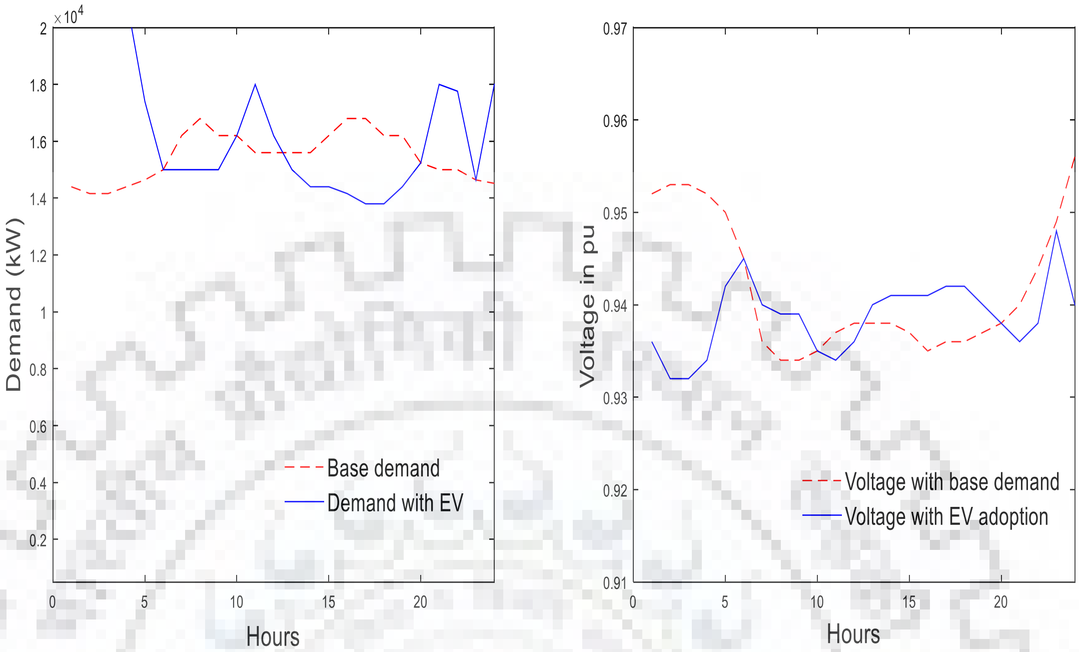


Fig 3.3: Demand and voltage pattern in case of profit maximization scenario.

3. Power factor control scenario: In this mode the main motive is to avoid the voltage of a node below a certain predefined value by injecting sufficient reactive power into the grid instead of charging the PEV with dumb charging scenario.

- **Demand and voltage profile:** The curve 1 of Figure 3.4 shows the variation of active power demand with and without PEVs and follows the pattern as expected, demand with PEV integration is more during the evening till early morning. By instructing PEVs to charge in the power factor control mode, the demand is spread out over a longer time period, which in turn reduces the peak in demand significantly. The reactive power demand pattern is shown by curve 2 of Fig 3.4 which depicts that there is a sufficient amount of power injected to the node between 18:00 to 02:00, this shows that during this time only when PEVs are plugged to charge there is a possibility that voltage at any node falls below 0.935 pu so that charging can be done under power factor control scenario and hence voltage can be maintained to an optimum level as shown by curve 3 of Fig 3.4.

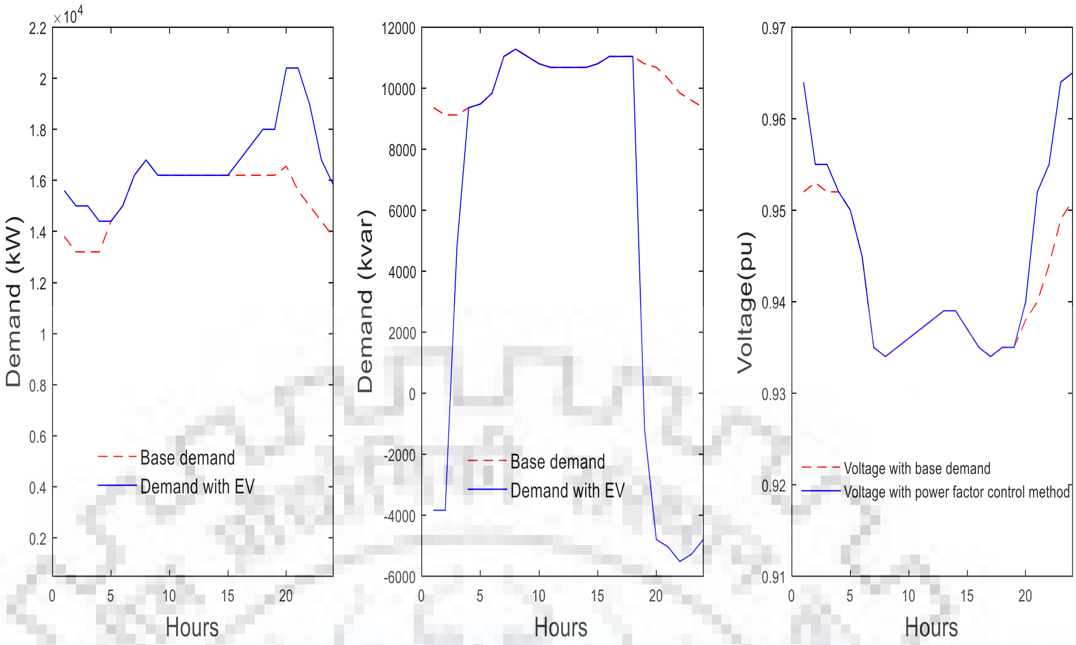


Fig 3.4: Active, reactive power demand and voltage profile for power factor control scenario.

3.5 Cost estimation

The charging cost for all the three scenarios can be calculated using the following relation

$$C(t) = \left(\beta 1 \ + \ \beta 2 \ * \ \alpha^{\frac{P_{sys}^{t} - P_{avg}}{P_{avg}}} \right) * 6.39 \ \ \text{DKK/kWh}$$

Where β_1, β_2 and α are real time price parameters with

$\beta_1 = 0.1$ \$/kWh, $\beta_2 = 0.2$ \$/kWh, $\alpha = 10$

P_{sys}^{t} = Demand from the grid for a particular infrastructure.

P_{avg} = Average load demand from the grid.

1 US\$ = 6.39 DKK.

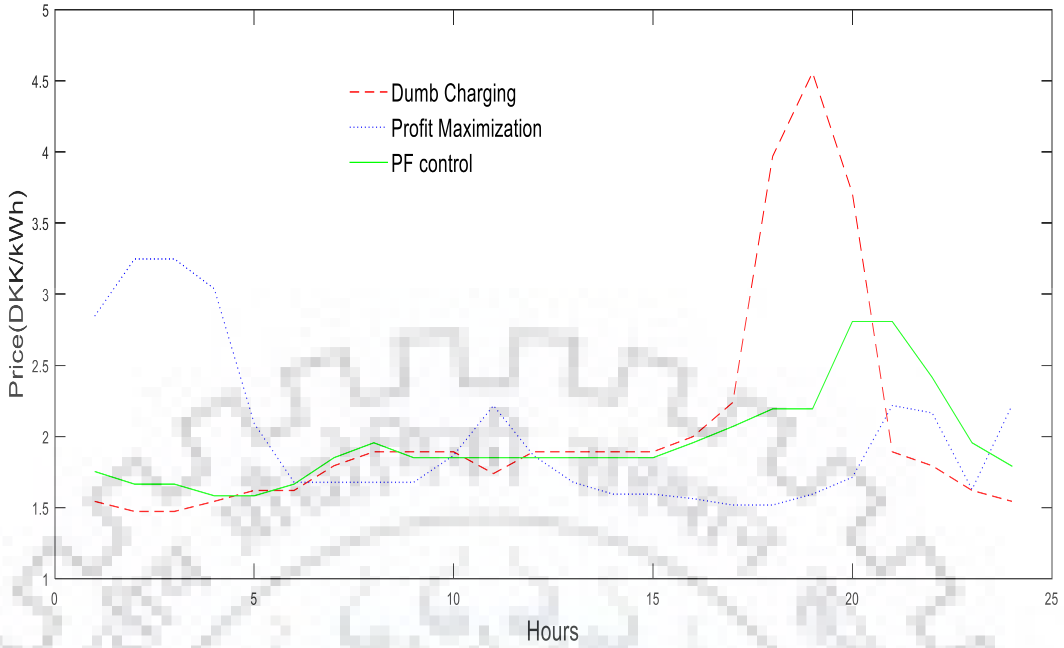


Fig 3.5: Cost comparison for all three scenarios.

It is clear from the fig 3.5 that average cost in case of dumb charging is greatest among three as PEVs are just plugged in for charging all over the night without involving any strategy. During the day time grid services are allowed for profit maximization scenario hence power is sold back to the grid which makes the effective cost lesser, but when the cost of electricity is less during the night the PEVs are only allowed to charge due to which effective cost increases. Price in case of power factor control scenario lies in between to that of other two. When voltage limit is violated at any node PEVs at that node are instructed to supply reactive power to the grid hence bringing back the voltage to the optimum level and so its cost is also lesser than dumb charging scenario.

3.6 Comparison

There are some parameters based on which these three scenarios can be compared. These parameters are *maximum demand, variation in demand* (P_{var})*, increase in peak demand, lowest voltage recorded*.

1. Maximum demand

Comparison is made based on bar graph as follows:

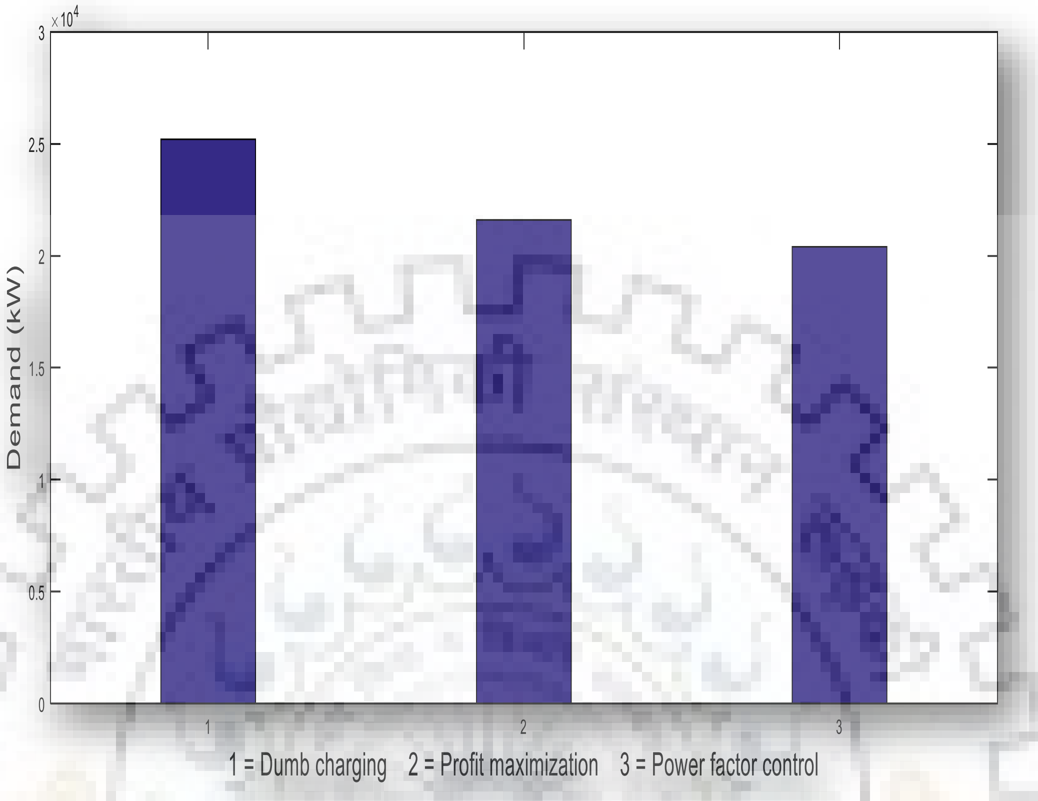


Fig 3.6: Maximum demand of each scenario.

It is quite clear that dumb charging data will have maximum demand during the charging of PEV, the other two scenarios will have almost comparable maximum demand as shown.

2. Variation in demand

Variation in demand (P_{var}) is calculated as

$$P_{var} = \left(\frac{P_{max} - P_{min}}{P_{avg}} \right) * 100$$

P_{max} = Maximum power demand with the integration of PEVs.
P_{min} = Minimum power demand with the integration of PEVs.
P_{avg} = Average power demand with the integration of PEVs.
P_{var} is calculated for each of the scenario and following result is obtained

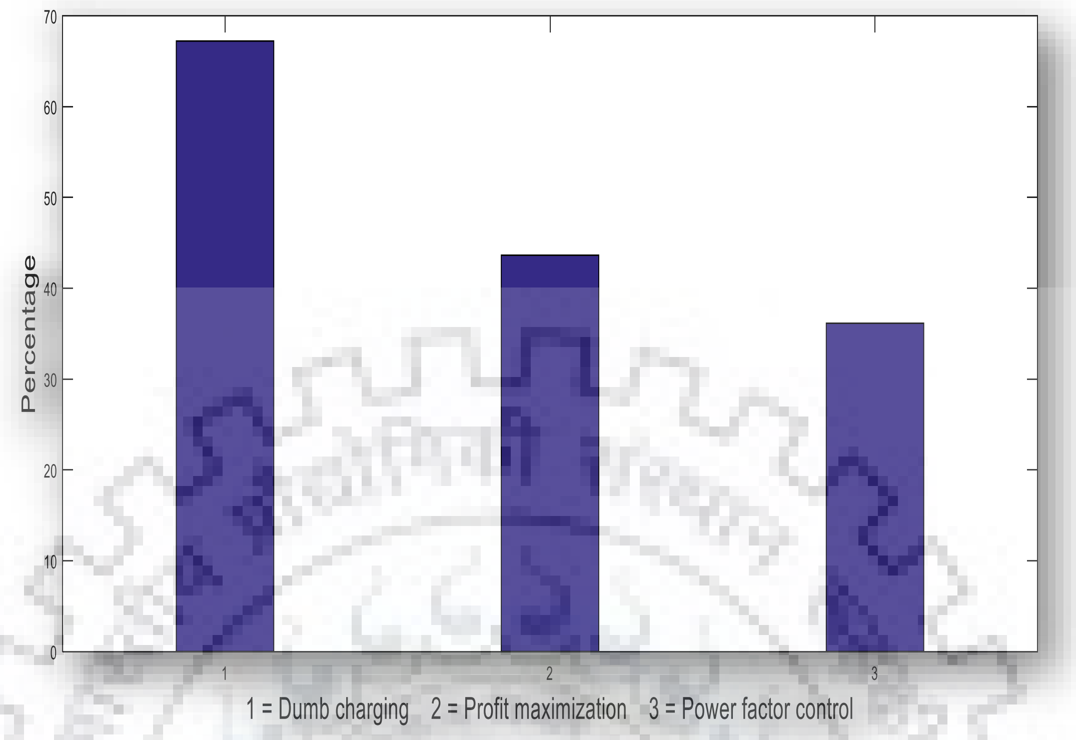


Fig 3.7: Variation in demand of each scenario.

Bar graph shows that variation in demand for dumb charging scenario is quite large as compared to that of profit maximization and power factor control scenarios. The variation in demand for the later ones is almost same. This result for the profit maximization scenario is because of its ability to perform V2G services

3. Increase in peak demand

The increase in demand (ΔP) is calculated as

$$\Delta P = \left(\frac{P_{max} - P_{maxb}}{P_{maxb}}\right)*100$$

P_{maxb} = Peak base demand.

ΔP is calculated for each scenario and the following result is obtained

Fig 3.8: Increase in peak demand of each scenario.

The demand pattern improves for both profit maximization and power factor control scenario compared to the dumb charging scenario. Power factor control scenario has the lowest change in peak demand among the two.

4. Lowest voltage

The value for lowest voltage recorded for each scenario is

For Dumb charging, v = 0.915 pu.
For Profit maximization, v = 0.932 pu.
For Power factor control, v = 0.934 pu.

The value for the lowest voltage was a bit higher in the power factor control scenario than the profit maximization scenario.

3.7 Conclusion

In case of uncontrolled PEV charging, the profile of the charging demand is highly dependent on the driving pattern of the vehicle throughout the day. According to the statistical data used in this thesis, the majority of the vehicles return from the last journey between 17:00 and 20:00. In the absence of smart charging strategy, this leads to a high peak in demand during that time. As the base demand pattern is also at peak during that time, the EV demand can easily be synchronized with the peak in the base demand.

Two smart charging scenarios are studied in this thesis; the *profit maximization* scenario and the *power factor control* scenario. The dumb charging scenario is taken just as a reference in which the owners just plugged their PEVs for charging without any prior strategy. For both smart charging strategies, it is observed that the maximum demands at all demand nodes in the power system were reduced. This is mainly because in dumb charging scenario significant number of vehicles are charged in a limited timeframe, while in case of other charging strategies charging is spread over a longer timeframe.

In profit maximization scenario, adding PEVs charging demand to the existing base demand causes the demand and price curve to flatten and it also reduces the variation in demand and change in peak demand. Also the average cost of this scenario comes out to be lower than other two due to its ability to perform V2G operations.

In the power factor control scenario, the EVs are assumed to charge as in the dumb charging scenario as long as there are no voltage violations at any of the demand nodes. The lowest voltage is taken to be 0.935 pu, and the lowest voltage recorded was 0.934 pu hence power factor control charging is done. The variation in demand and change in peak demand comes out to be lowest in this case.

The study does not prove that which charging strategy is the best and should be taken into account, rather it compares the strategies on the basis of various factors and results are obtained using MATLAB coding.

Chapter 4

Swarm Intelligence for Developing an Optimal Charging Profile of PEVs

4.1. Introduction

The individual energy available in the PEV battery is not a quantity that is large enough to make any significant change to the grid in terms of power injected. For example, the Chevy Volt has a maximum available energy capacity of 16 kWh[2] . Thus, it is necessary to take a number of PEVs together so that they represent a large kW load and have the ability to make a significant contribution to the grid when the need arises. This particular action can be facilitated with the help of the aggregator concept. The aggregator is the interface between the PEV and the ISO. The aggregator keeps a track of the total aggregated load of the PEVs and the grid demand as given by the ISO at any given time. These parameters combined with the electricity rates at any particular hour help the aggregator determine whether or not a transaction (V2G/G2V) will take place. This relationship between the aggregator, PEVs and ISO has been illustrated in below Fig 4.1:

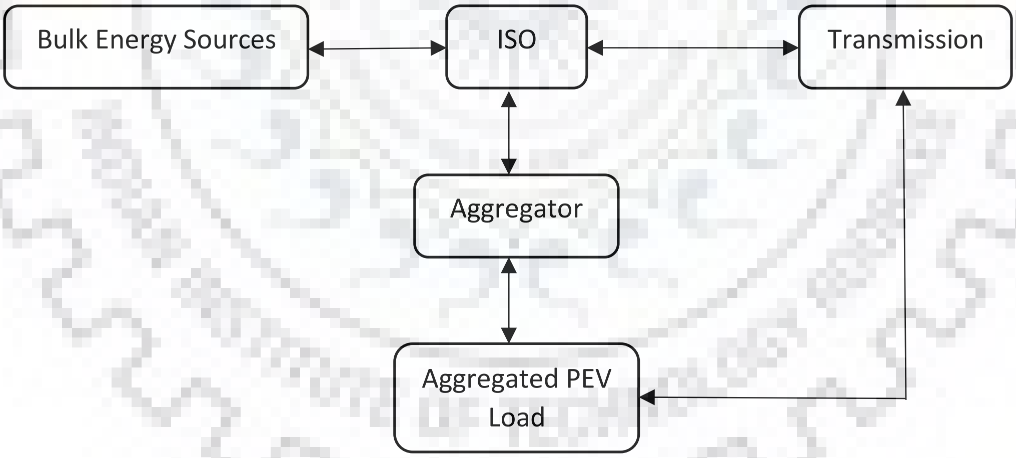


Fig 4.1: Framework for V2G transactions for aggregated EV Loads

In the future smart grid environment the PEV user preferences should have a bearing on aggregator behaviour. For example, the PEV user will have the option of whether or not to allow their vehicle to participate in aggregation. The PEV user could reserve the right to use their PEV in only a dumb charging scenario i.e. the PEV will automatically start to charge when it is plugged in.

It has already been mentioned that a major attraction of V2G technology is that it could be used by the PEV user to earn revenue. This revenue could be maximized by having multiple V2G transactions with the grid. It is proposed that the PEV should be subjected to an intelligent charging/discharging schedule.

This optimized charging/discharging schedule would serve two primary objectives

(i) Maintaining a profit margin for the PEV user

(iii) Reducing burden during peak load hours thus meeting grid requirements

4.2. Problem Formulation

In this study single transaction is termed as one time charging and discharging with the grid.

It will take place using the Regulation Market Clearing Price (RMCP) [2] . Furthermore, the following three possibilities may take place: (i) Charging (ii) Discharging and (iii) No transaction with the grid. The PSO algorithm is used to generate a charging/discharging profile which would be applicable to every PEV that is plugged-in.

This study can be used to develop a scalable parking lot where aggregate load of fleet of vehicles do transactions during office hours where most of the cars stay between 10 am to 6 pm. The significance of studying PEV charging/discharging patterns for this specific time slot is significant because in a future smart grid scenario aggregated PEV loads could be used for load curtailment during the peak load demand which takes place during the said time-frame. In the future smart grid environment it can be expected that aggregated loads of PEVs in office spaces will be used for regulation [3] .

Following are equations used for the whole computation:

$$C_t = \frac{P_t * (SOC * KWH_{max} - KWH_{available})}{\eta_{charge}} \tag{3}$$

$$R_t = P_t * (KWH_{available} - SOC * KWH_{max}) * \eta_{discharge} \tag{4}$$

$$\text{Maximize Profit} = \sum_{t=1}^{T} (R_t - C_t) \tag{5}$$

$$\triangle \text{SOC} = \eta * \frac{KWH_{available}}{KWH_{max}} \tag{6}$$

$$SOC_t = SOC_{t-1} - \triangle \text{SOC} \tag{7}$$

$$SOC_t = SOC_{t-1} + \triangle \text{SOC} \tag{8}$$

Table 4.1 shows the definition of respective notation used in above equations.

Table 4.1: Parameters definition

Symbol	Definition
C_t	Resulting cost of charging that vehicle
R_t	Revenue made by selling from that vehicle
P_t	Price at hour t
t	Optimal buy/sell time hour
$kWh_{available}$	Kilowatt-Hour energy in the battery
kWh_{max}	Maximum battery capacity
SOC	Departure SOC
η_{charge}	Charging Efficiency
$\eta_{discharge}$	Inverter Efficiency

4.3. Results and Discussions:

To reduce the dimensionality of the problem we have assumed that each PEV battery have fixed charging and discharging efficiency of 85%. And also, only for single transaction with the grid case each EV is assumed to have 70% of SOC available in the battery so that it can be used as V2G and G2V at the optimal instants found out by PSO. Table 4.2 shows the limits of different parameters of electric vehicle.

Table 4.2: Range of Parameters for each Electric vehicle

Parameters	Minimum	Maximum
Battery Capacity (kWh)	10	25
Available Capacity (%)	50	100
Arrive Time	1st hour	23rd hour
Departure Time	2nd hour	24th hour

4.3.1. For Single transaction of charging and discharging:

The optimal charging profile obtained by using PSO has been utilized for mapping the SOC after having V2G and G2V transactions in this case. It can be seen that the PEV have sufficient amount of SOC available within it during the time of departure. It can also be seen that the vehicle is able to successfully supply power to the grid and taking power from the grid during optimal hour of charging/discharging for profit maximization. The remainder of the times the PEV is seen to be operating in CS (charge sustaining) mode.

In this methodology of single transaction of charging/discharging, the transactions with the grid are limited to only 2. Every vehicle has a desired departure SOC set to be 70%, so that after transactions with the grid, it has sufficient amount of SOC available to reach back to their place. As it is single transaction so surely profit is limited but the schedule of charging and discharging is very easy to determine. For simplicity each vehicle charging and discharging efficiency is maintained to be constant at 85%. The profit that the PEV user will earn will be the difference of revenue obtained by the user while discharging the available battery storage back to grid at optimal discharging hour and the cost incurred by the user while charging at optimal charging hour. The cost and revenue are calculated from equations (3) and (4) at optimal hour of charging and discharging.

Table 4.3: Optimal charging and discharging instants for single transaction

PEV ID	Arrival Time	Departure Time	Optimal Charging Instant	Optimal Discharging Instant	Objective Function Convergence value
1	2	13	3	7	0.168
2	2	19	3	18	0.2401
3	2	22	17	18	0.2861
4	9	22	17	18	0.2861
5	14	20	17	18	0.2861
6	8	19	17	18	0.2861
7	6	15	15	7	0.1834
8	11	22	17	18	0.2861
9	9	22	17	18	0.2861
10	13	22	17	18	0.2861
11	4	10	4	7	0.099
12	5	11	10	7	0.076
13	6	14	10	7	0.076
14	19	24	20	23	0.114
15	2	24	3	23	0.229

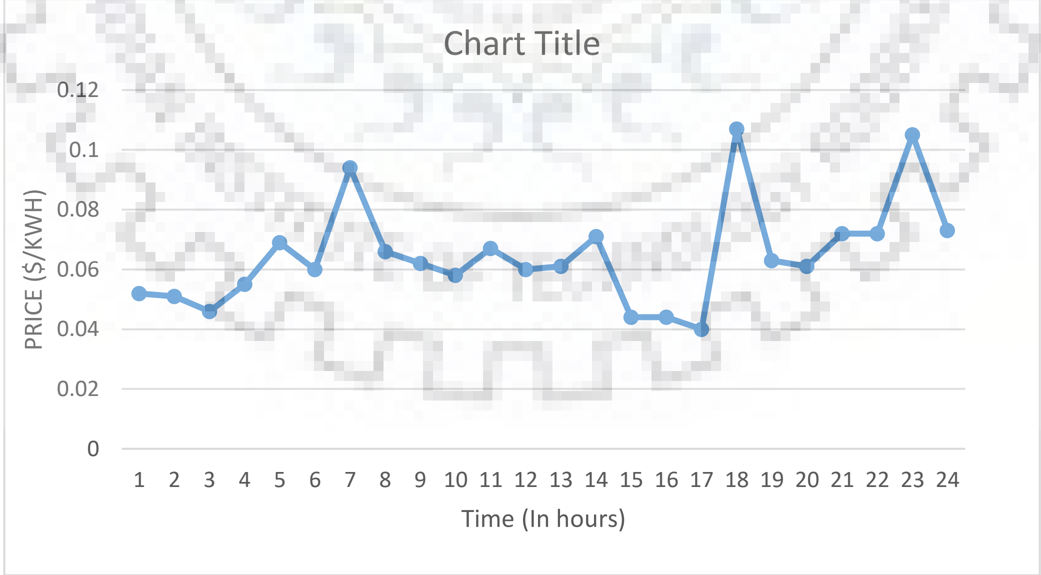


Fig 4.2: Price curve in $/KWH vs time in hours

Table 4.3 shows the different PEV coming at different arrival and departure time. Based on their arrival time, departure time, energy available inside battery, Price of unit etc. optimal charging and discharging instants are found out by using PSO algorithm. As this study is limited to single transaction of charging and discharging throughout the day, so single optimal charging and discharging instants are found out by optimizing technique. It can be seen from the price curve that based on the PEV presence inside the parking lot, the PEV takes power from the grid (i.e. charging) during low price of unit and supply power back to grid at the time of high price of unit. Fig 4.3 and Fig 4.4 shows the change in the SOC of the battery after single transaction of charging and discharging at optimal charging and discharging instants. For simplicity, charging and discharging efficiency of the batteries are taken to be same and initial SOC is taken to be 70%. That's why after the transactions it comes back to the same level. Fig 4.3 and Fig 4.4 shows only the behaviour of SOC after transaction.

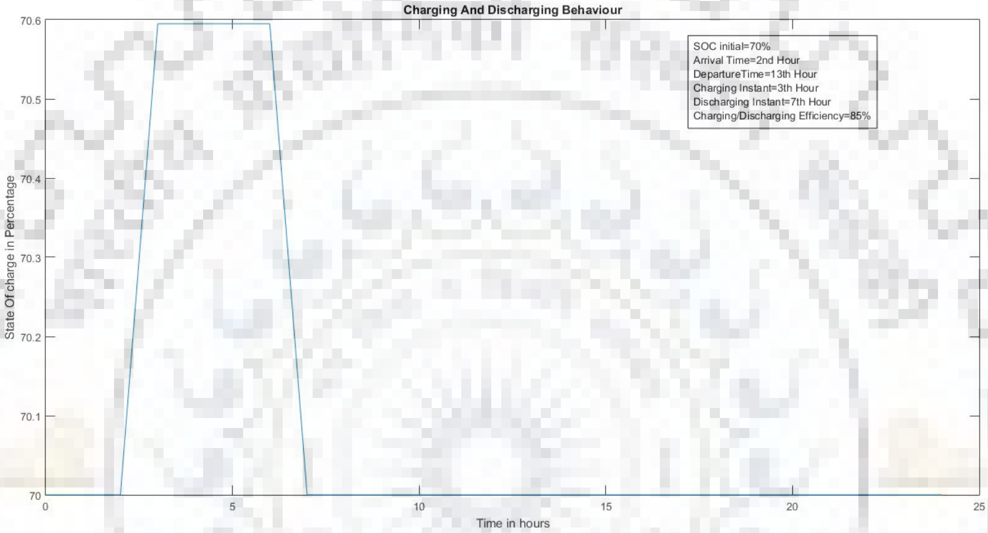


Fig 4.3: Charging And discharging Behaviour for EV 1

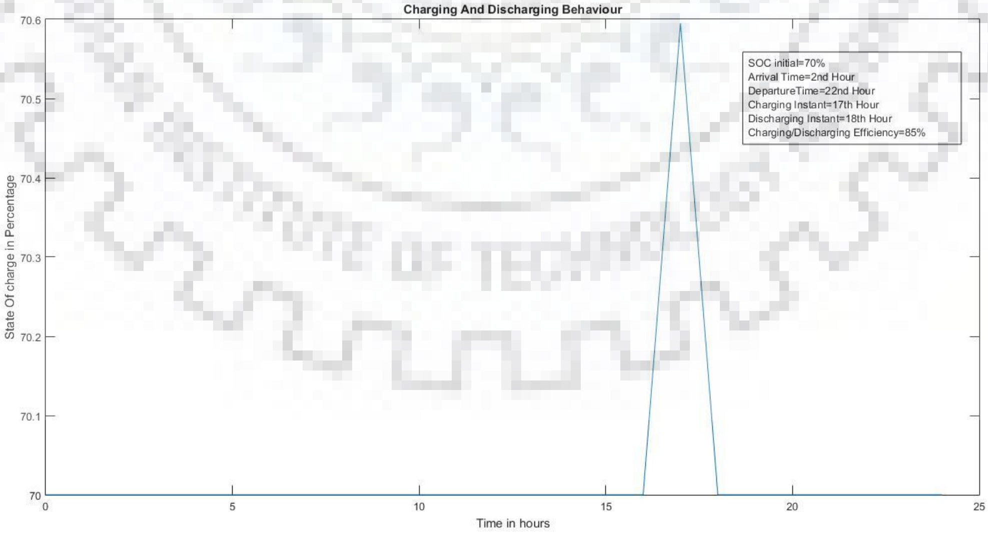


Fig 4.4: Charging And discharging Behaviour for EV 9

A. For single transaction of charging and discharging of 50 EV:

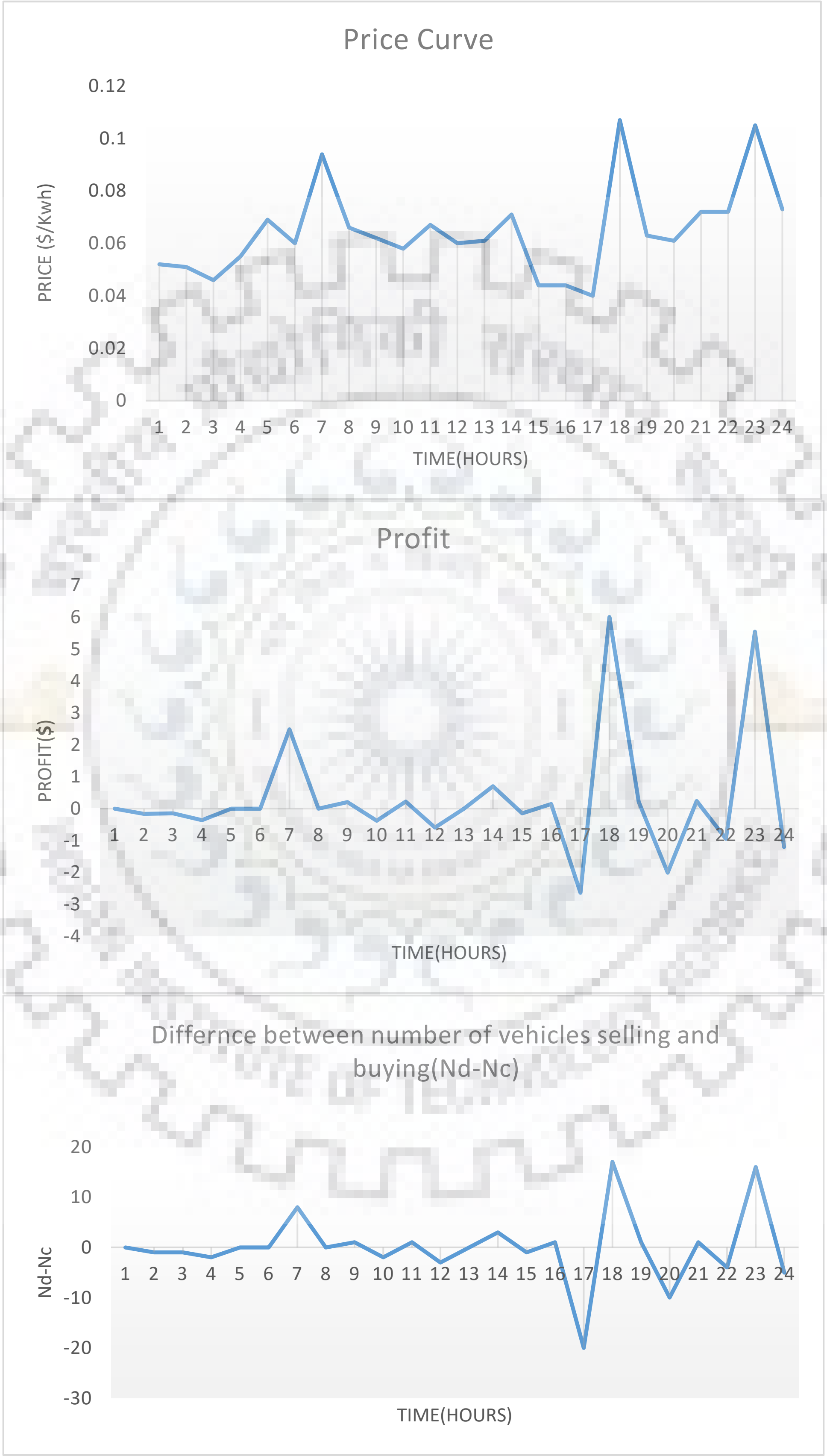


Fig 4.5: Case study for 50 Number of EVs

Fig 4.5 represents case study of 50 EVs of an intelligent parking lot. The arrival and departure time of EVs are assumed to be random variables. Batteries of all EVs are assumed to be same. There is a restriction of only single time charging and discharging of each EV throughout the day. ‘Number of vehicles buying and selling’ graph shows total 50 EV gets distributed among the whole time period for charging/discharging depending upon their arrival and departure time. Difference between number of vehicles selling and buying (Nd-Nc) is highest at 7:00th and 18:00th hour which means that V2G transactions are more in number then G2V transactions at these particular hour satisfying all constraints. Number of vehicles selling power to the grid are more concentrated in the region between 17:00 to 19:00 because prices are at its peak at that time .So the parking lot is doing G2V transactions i.e. charging of EVs during off peak hours and V2G transactions i.e. selling of electricity during peak hours. Between 8:00 to 10:00 the prices are low, so at that time power flow back to grid is more or less zero.

B. For single transaction of charging and discharging of 500 EV:

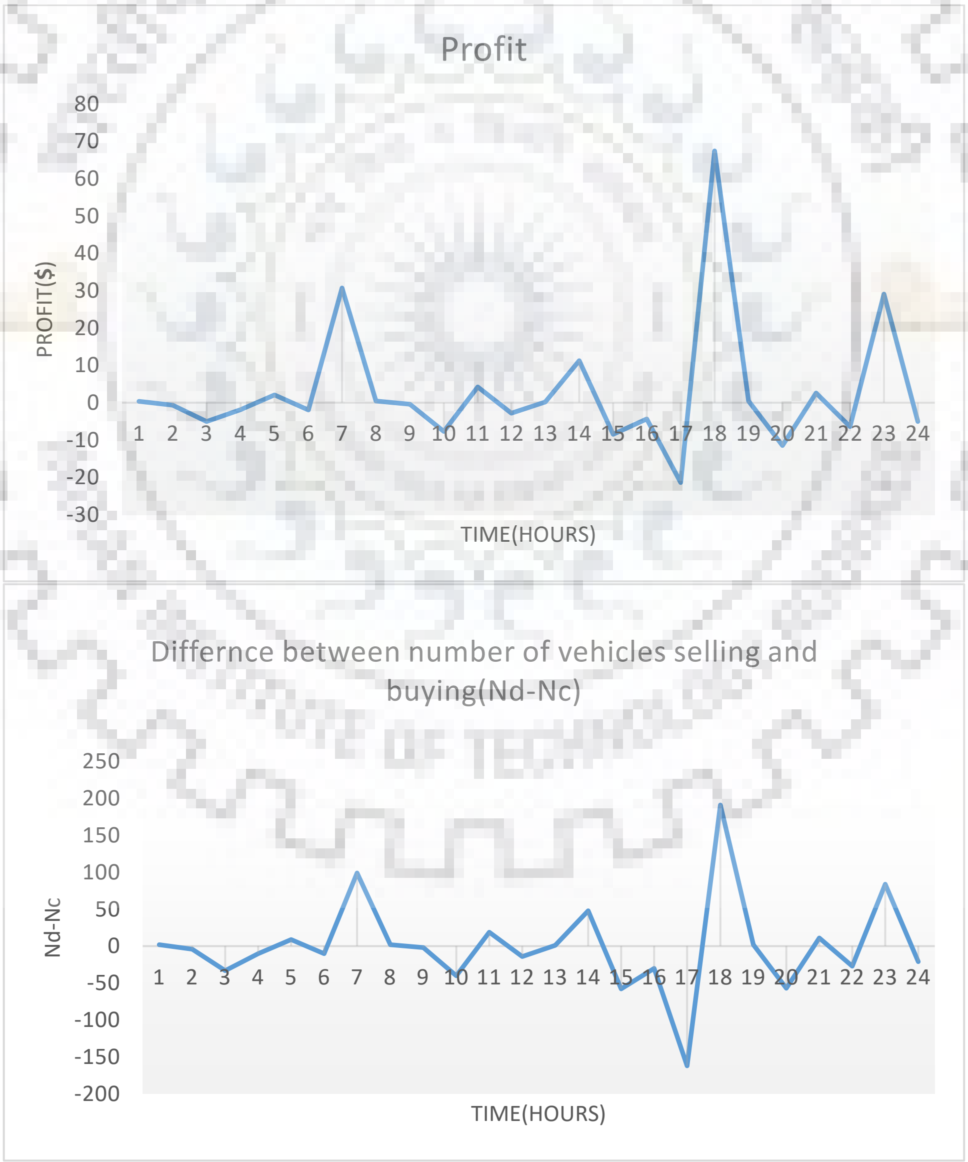


Fig 4.6: Case study for 500 Number of EVs

Fig 4.6 shows the total fleet of 500 EVs. With the increase number of EVs the profit margin increases which tells that the number of V2G transactions increases. We can see that charging of EV i.e G2V transactions are more flatly distributed almost at every hour but discharging are more concentrated at peak hours mostly. This is due to algorithm develop which distribute charging/discharging hours while satisfying conditions like price of unit,70% of departure SOC available while leaving etc.

4.3.2. For multiple transactions of charging and discharging:

To increase the profit margin and to achieve the peak shaving of power grid by having the bidirectional flow of energy between Grid and PEVs, multiple transactions is essential. With the given price curve ,formulation is done such that when prices are high the basic load power is high and when prices are lower the basic load power is low. So for finding out multiple optimal charging and discharging instants in a given day, whole price curve is divided up into three intervals: Low price interval is between 24:00-10:00, Medium price interval is between 10:00-18:00 and high price interval is between 18:00-24:00 respectively. According to arrival time, departure time and the initial SOC available to the upcoming PEV, the optimization algorithm defines the charging and discharging status of every PEV user independently and then find out the optimal charging and discharging instants. In this multiple transactions, we have assumed the departure SOC must be 60%.

Following are the four cases which algorithm will check for every PEV at every hour based on the arrival and departure time of PEV to do optimization:

Case 1:
T=10 is the state assign to high price interval. During high price interval if SOC<=0.6, PEV charges to increase the SOC to 0.6. After attaining a sufficient amount of SOC, if still it is present in high price interval, it will charge again when low price interval commences.
Case 2:
When SOC>0.6 and PEV present in high price interval, then it will discharges until its SOC reaches up to 0.6. If it is still present in high price interval, it will charge again when low price interval commences.
Case 3:
T=01 is the state assign to normal price interval. If SOC<=0.8, PEV charges up to attain SOC=0.8. If it still presents in the normal price interval or going towards high price interval, PEV would charge during normal price interval.
Case 4:
T=00 is the state assign to normal price interval. During low price interval, PEV charges to SOC=1.

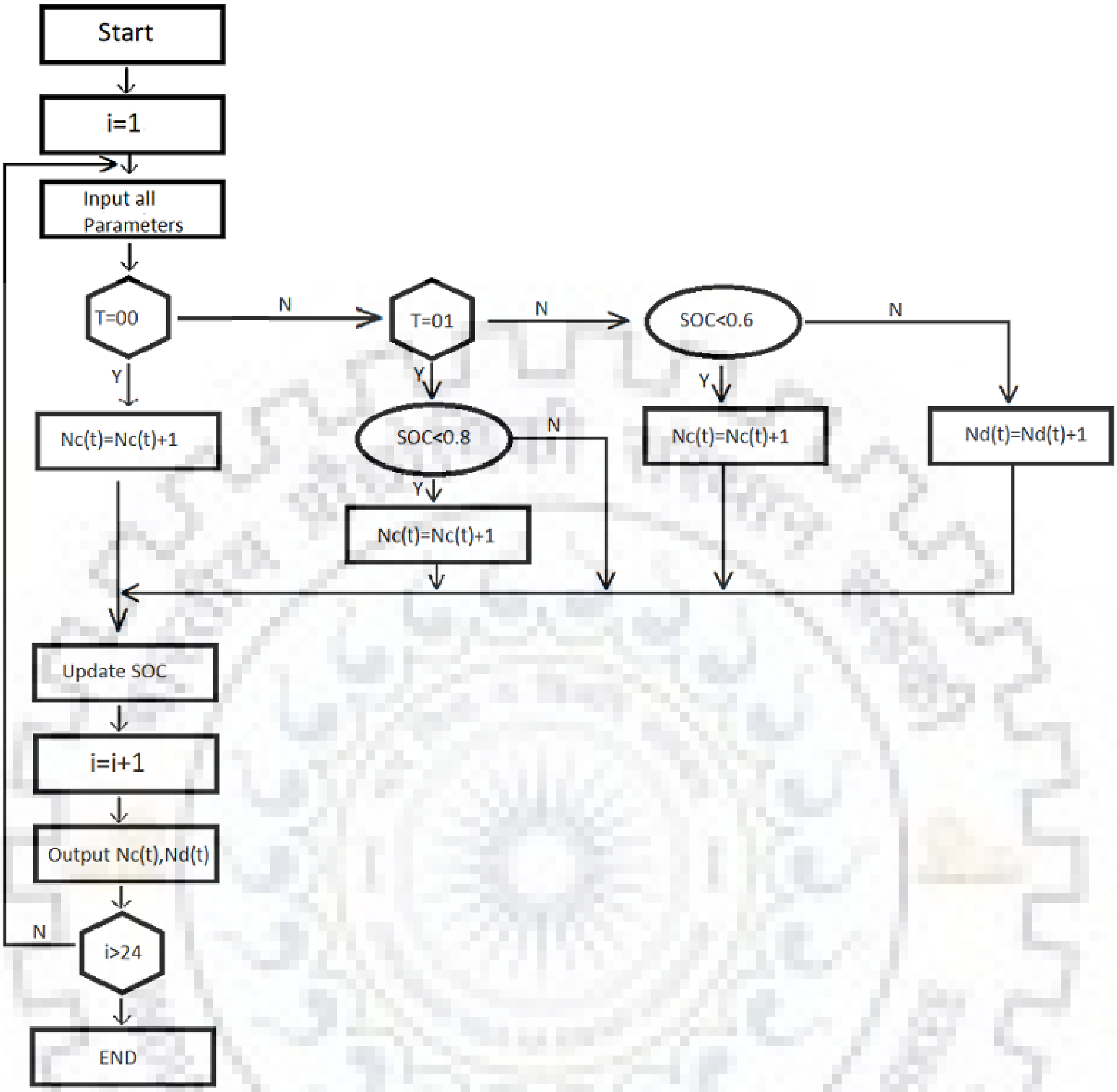


Fig 4.7: Calculating number of charging and discharging PEV

Above algorithm represents the flowchart for calculating the number of PEVs charging and discharging at every hour. In Case of PEV user profit, number of charging slots are not restricted. They are assumed to be infinite. Nc(t) represents the number of charging PEVs at respective hour and Nd(t) represents the number of discharging PEVs at respective hour. For the time sake main motive is to maximize the profit so the charging and discharging power is constantly equal to 3.3kW. For the simplicity the battery of EV is assumed to be of Nissan leaf 2017S having acceptance rate 3.6 kW (on board charger limit).Battery size is 30 kWh. Charger is assumed to be of level 2 charger with input of 240V AC, 15 A current. So according to initial SOC, Price of electricity, arrival and departure time, optimal charging and discharging instants are found out by maximizing the objective function. So by this number of charging and discharging PEVs at every instant are sorted .After every hour SOC of every PEV is updated.

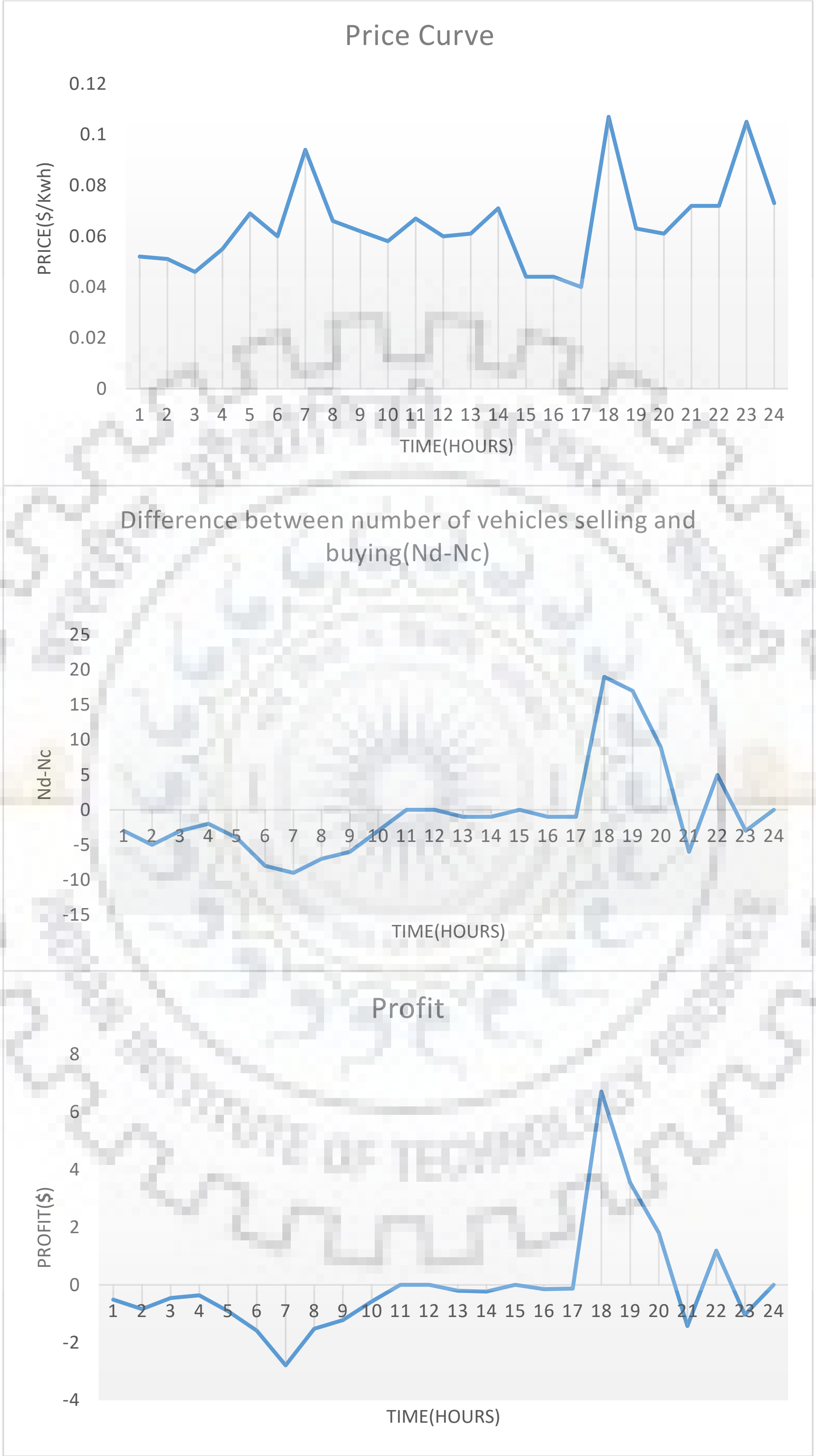
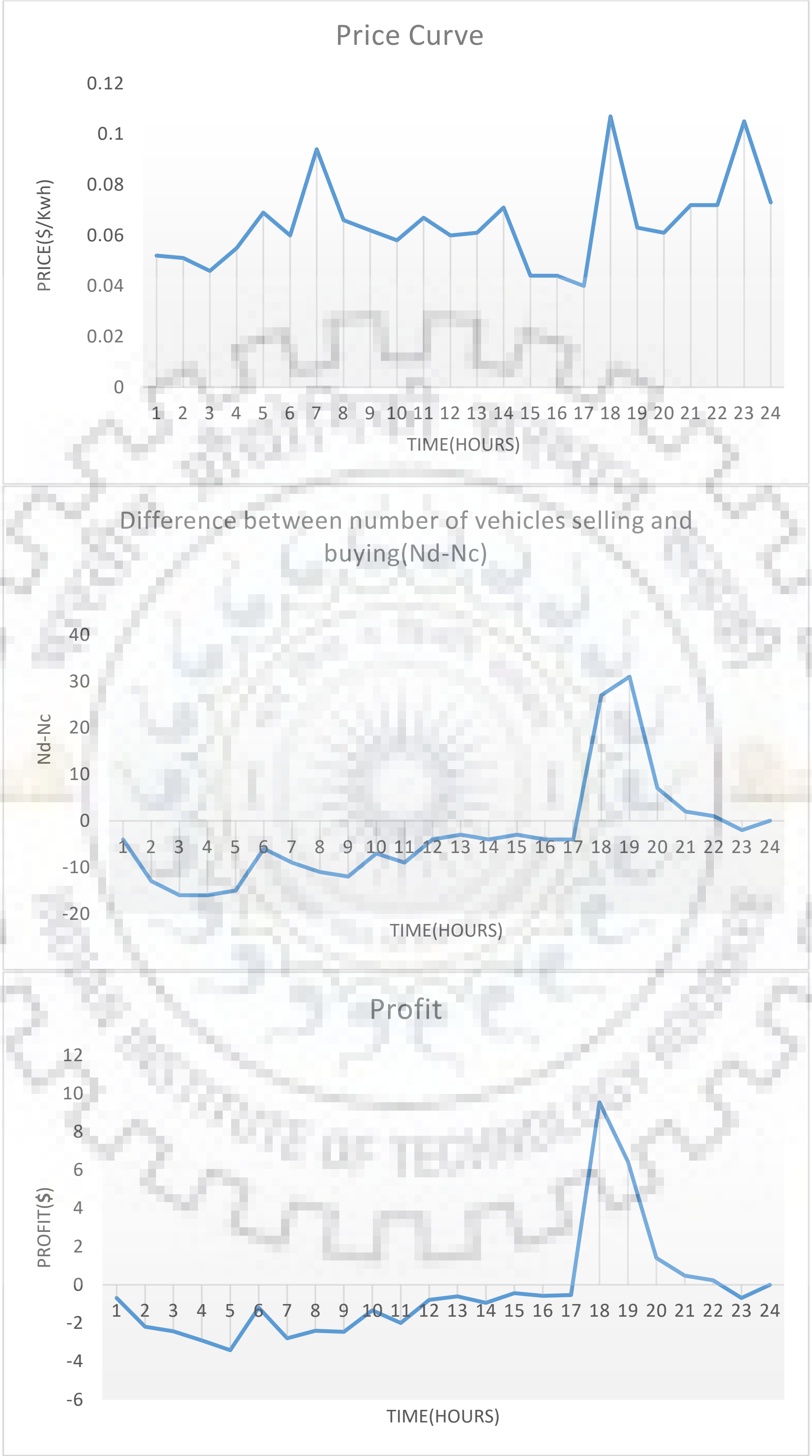


Fig 4.8: Case study for 50 Number of EVs


Price Curve

Difference between number of vehicles selling and buying(Nd-Nc)

Profit

Fig 4.9: Case study for 100 Number of EVs

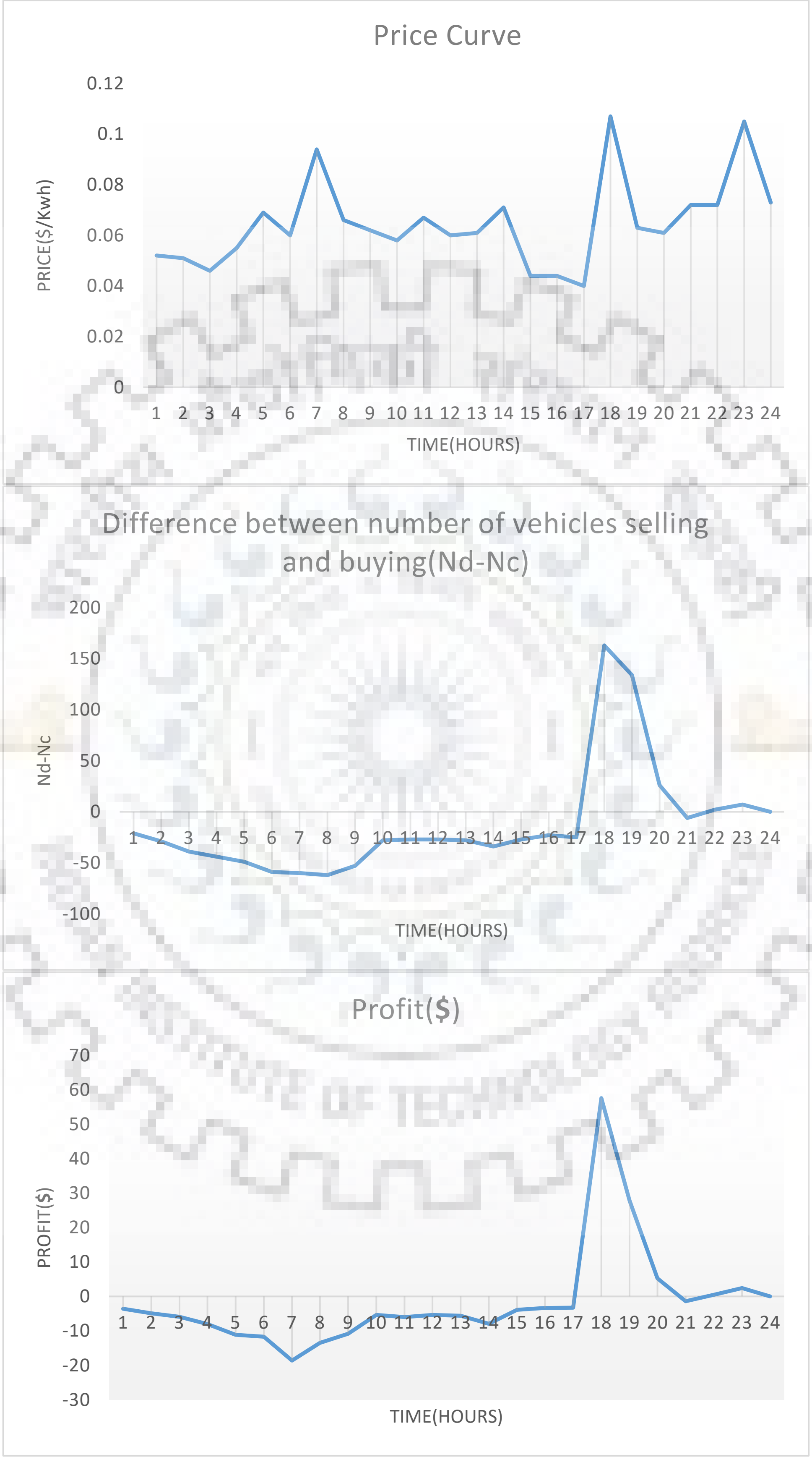


Fig 4.10: Case study for 500 Number of EVs

Fig 4.8 to fig 4.10 shows the multiple transactions with the grid i.e. multiple time charging and discharging in particular time frame and depends upon the optimal charging and discharging instants. Fig 4.5 shows the case study of 50 PEVs of single transaction only and Fig 4.8 shows for multiple transactions with the same fleet of PEVs of 50. By comparing with the single transaction with the grid, the profit of PEV users individually has increased significantly in multiple transactions with the grid. The number of vehicles going under V2G transactions have increased in number during high price hours and number of vehicles going under charging mode i.e. G2V transactions have increased in number during low price hours, thus satisfying constraints and meeting objective according to the structural flow of the algorithm. Satisfying the load or helping the grid during high peak hours and charging during low hours helps the load profile to gets flatten and overcome the possibility of congestion. This procedural flow of meeting the objective helps in peak shaving of load profile. Fig 4.9 and Fig 4.10 shows the case study of 100 and 500 number of PEVs. With the increase in number of PEV user, the benefits as a whole gets increased as seen from the profit curve of each of them. As the number of charging points are not restricted in these transactions, that is why it is more inclined towards the PEV user benefit algorithm and indirectly benefits the grid. But if we include the practical aspect i.e. limited number of charging and discharging points and include the branch constraints which is carrying power to and fro, then the algorithm will cover the technical and economic aspects of PEV user and power grid both as a whole.

Chapter 5

Optimization of Charging and Discharging Power of PEVs

5.1. Introduction

The need of optimal charging and discharging power is very essential. Large number of Electric vehicles when connected to grid at same time might cause the deficiency of electricity and also increases the power fluctuation in the branches [12],[13] . To deal with this situation an optimal strategy is proposed which maintains the power though branches within permissible limits and also benefits the PEV user. PSO (Particle swarm optimisation) algorithm is used to carry out the optimal charging and discharging powers. The algorithm increases the benefits of PEV user and also ensure the stable operation of the grid. So by considering the Initial SOC value, arrival time, departure time and current electricity price the problem is formulated as a maximum profit for PEV user and benefits power grid.

5.2. Mathematical Model for Optimization

The goal of optimization is to minimize the fluctuation of Daily load curve in distribution network and to maximize the overall profit of PEV user. After addition of electric vehicle load i.e. during charging and discharging, power transmission constraints must be satisfied. So by acquiring this optimal charging and discharging strategy, stable power transportation via each branch is maintained [14].

In the previous chapter the objective function mainly focusses on maximization of PEV user's profit. But in this chapter the objective is to increase the profit of power grid companies by reducing the power fluctuations and also reduce the peak to valley difference of the load curve after addition of PEV load. This objective function of this optimal strategy is described in a function as

$$g_1=\text{minimize}\sum_{t=0}^{T}(P_{c,t} * N_{c,t} - P_{d,t} * N_{d,t} + P_{load,t} - \bar{P})^2 \qquad (9)$$

Where $P_{c,t}$ represents charging power, $P_{d,t}$ represents discharging power, $N_{c,t}\ and\ N_{d,t}$ represents the number of electric vehicle charging and discharging at particular time instant t, $P_{load,t}$ represents the load power without PEV addition to the existing system at time t, $\bar{P}$ represents the average load power over a day without PEV load. $P_{load,t}$ and $\bar{P}$ had taken from historical. Table 5.1 represents definition of different notation used. To meet the objective, the algorithm must follow the constraints at each time interval Δt which are as follows:

$$(SOC_{fin,h,t} - SOC_{ini,h,t}) * C_{max} * N_{c,t} \leq E_{total,t} - E_{load,t} \qquad (10)$$

$$P_{load,t} + P_{c,t} * N_{c,t} - P_{d,t} * N_{d,t} \leq P_{l,max} \tag{11}$$

$$P_{c,min} \leq P_{c,t} \leq P_{c,max} \tag{12}$$

$$P_{d,min} \leq P_{d,t} \leq P_{d,max} \tag{13}$$

$$0 \leq N_{c,t}^{S} \leq N_{max}^{S} \tag{14}$$

$$0 \leq N_{d,t}^{S} \leq N_{max}^{S} \tag{15}$$

Table 5.1: Symbol representation

Symbol	**Definition**
$SOC_{fin,h,t}$	Initial available SOC of PEV when it arrive at charging station h at time t
$SOC_{ini,h,t}$	Final available SOC of PEV while leaving charging station h at time t
C_{max}	Maximum capacity of PEV battery
$E_{load,t}$	Total energy used by load without Electric vehicle addition
$E_{total,t}$	Total energy in distributed network at time t
$P_{l,max}$	Maximum active power limit through transmission line or a particular branch l
$P_{c,min}$	Minimum limit of charging power of PEV
$P_{c,max}$	Maximum limit of charging power of PEV
$P_{d,min}$	Minimum limit of discharging power of PEV
$P_{d,max}$	Maximum limit of discharging power of PEV
$N_{d,t}^{S}$	Number OF PEV discharging at charging station S at time t
$N_{c,t}^{S}$	Number of PEV charging at charging station S at time t
N_{max}^{S}	Maximum charging /discharging ports available at station S

5.3. Algorithm for Power Optimization

Particle Swarm Optimization (PSO) technique is developed for power optimization of charging and discharging of PEVs [15] ,[16] . PSO is applied to find out the optimal charging power ($P_{c,t}$) and optimal discharging power ($P_{d,t}$) from a set of population which is randomly initiated. In a certain charging station, total charging power drawn from the grid and total discharging power can be calculated as

$$P_{c,total} = P_{c,t} * N_{c,t} \tag{16}$$

$$P_{d,total} = P_{d,t} * N_{d,t} \tag{17}$$

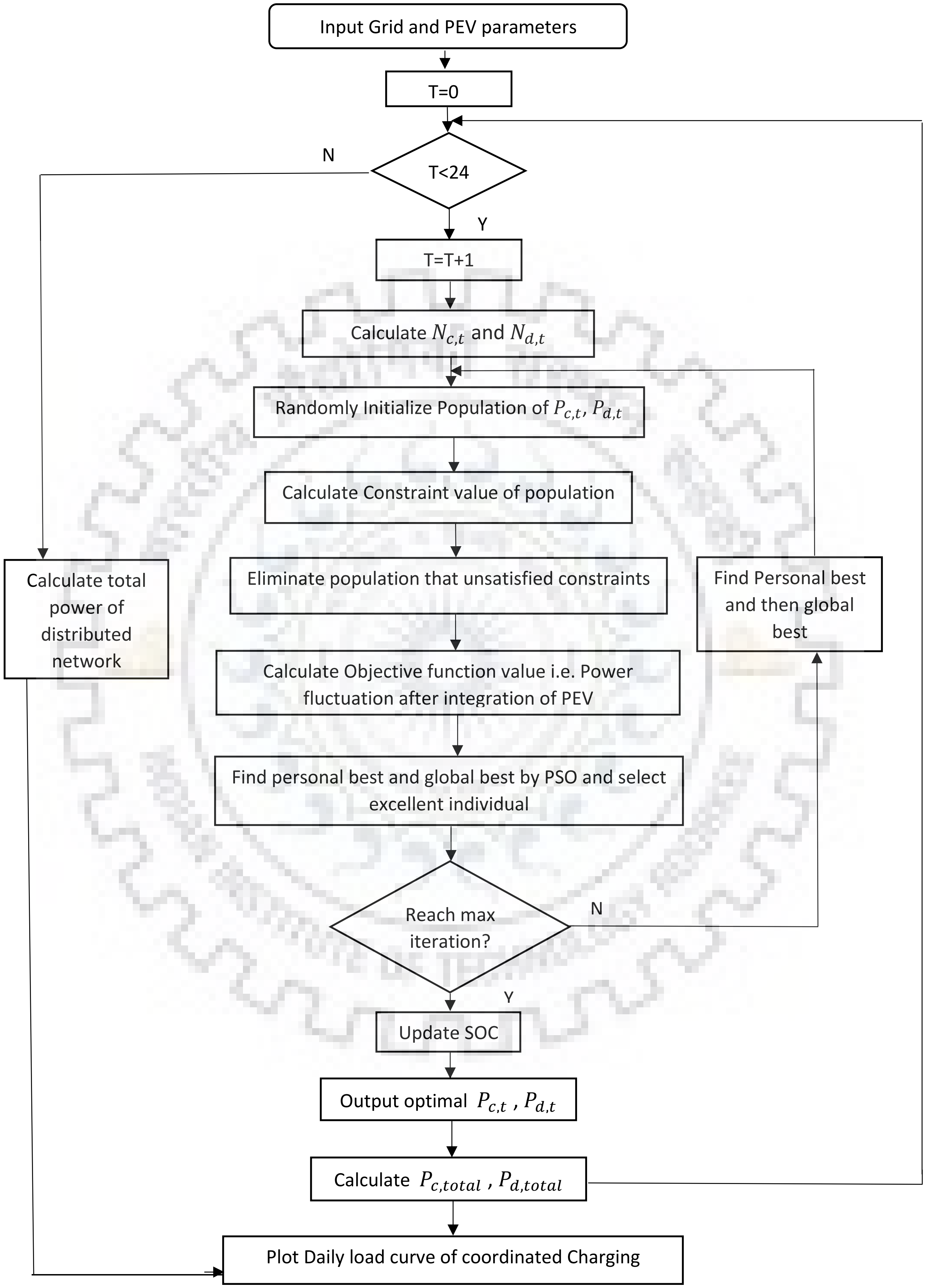


Fig 5.1: Flow Chart of Power Optimization algorithm

Where $P_{c,t}$, $P_{d,t}$ are the best solutions from the population initiated.
Constraint equation (10) takes care of condition that total energy taken while charging a fleet of PEVs must not surpass the surplus energy of distributed network. Constraint equation (11) takes care of branch safety while G2V or V2G transactions with grid i.e. while charging or discharging of the present PEV, the active power flowing through branch remains within its permissible limits. Constraint equation (12) and (13) takes care of health of the battery. It signifies that the charging and discharging power of PEVs remains within permissible limits at every instant of the 24 hr time period. The limit violation of charging and discharging power not only damages battery but also increases the fluctuation level inside the grid. Also if lower side limits i.e. $P_{c,min}$ and $P_{d,min}$ violates, then charging of a particular EV takes longer time. Constraint equation (14) and (15) takes care that the number of PEV at a particular charging station cannot increase the available capacity or charging/discharging ports.

5.4. Simulation and Results:

The Simulation is done in Matlab. For simplification, each electric vehicle battery taken is of Nissan leaf 2017 S. The characteristic sheet is provided in the reference [16]. Level 2 charger with rated capacity 240V AC/ 15A is used. Each EV charging and discharging power limits at every hour are 3kW<$P_{c,t}$<3.5kW, 3kW<$P_{d,t}$<3.5kW. On board charger limit is 3.6 kW.

Fig 5.2 shows the daily load curves of one branch. The historical load data is taken from reference [17]. The 'load without PEV' curve shows the historical daily load curve without PEV integration and other curve shows the daily load curve of the same branch with PEV integration but without any optimization strategy. So an uncoordinated charging increases the peak to valley difference. The difference is most severe during evening hours between 19:00 to 22:00. As the load requirement gets increased, power transportation through one branch gets increased which might causes damage of the branch. So charging/discharging must follows some strategy for protection of distributed circuit.

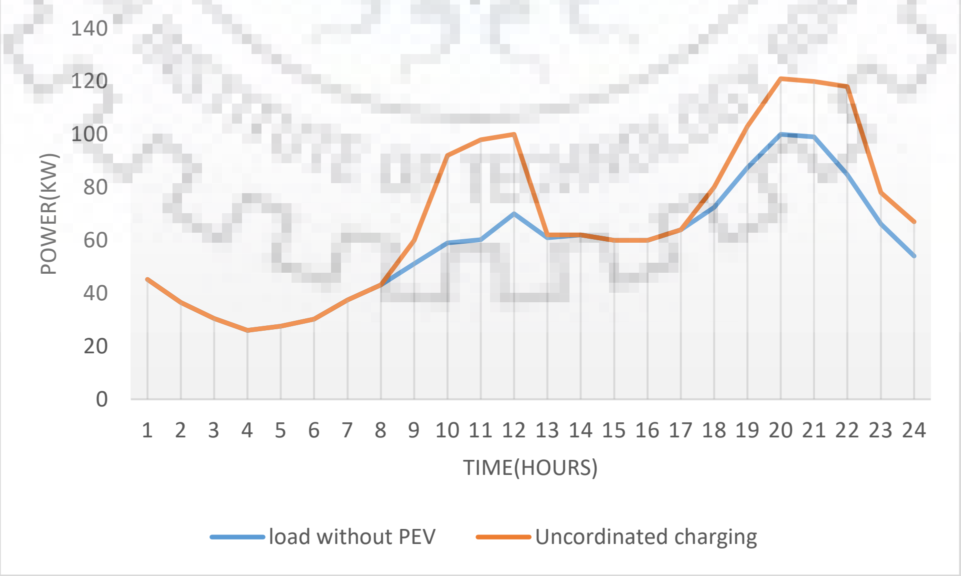


Fig 5.2: Load curve of one branch

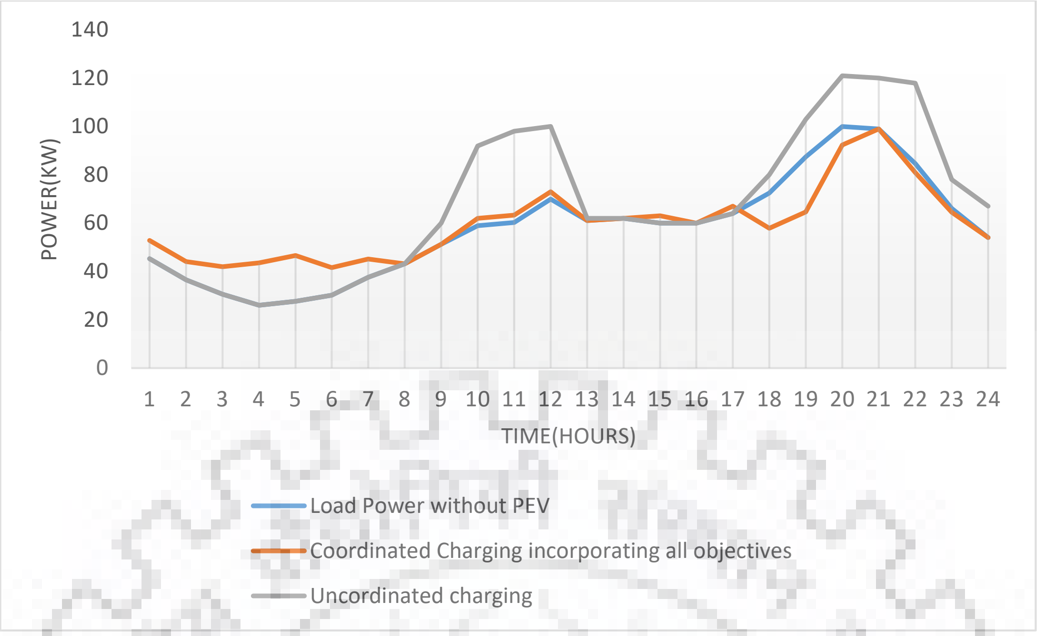


Fig 5.3: Load Power Curve after Power optimization Algorithm

The load curve in Fig 5.3 shows the power optimized coordinated charging. So by comparing the coordinated charging with uncoordinated charging it shows that peak to valley difference actually gets decreased in coordinated charging. The PEVs are going to charge more in off peak hours and discharges during peak hours. This charging/discharging behaviour significantly increases the stability of the branch thus distributed network as whole. Also the coordinated charging curve follows the load curve of branch in most of the time instants, so the objective of reduction of power fluctuation also met. During 1:00 to 8:00 most of the PEVs are going to charge depends on the random arrival, departure and initial SOC present in the battery and similarly by incorporating the same conditions, between 18:00 to 21:00 most of the PEVs are going to discharge. Thus V2G transactions during peak power hours support the grid and also increases profit to the PEV users. The reduction of power fluctuations is the result of power optimization strategy. The algorithm finds the optimal charging and discharging power at each hour throughout the day satisfying all constraints within permissible limits. Due to V2G system, the problem of shortage of electricity for satisfying the load actually vanishes and load curve gets smoother with this strategy. The load data of a particular branch is available on an hour basis. If data availability is half an hour basis, then the profile gets smoother.

Chapter 6

Conclusion and Future Scope

6.1 Conclusion:

The first model of profit maximization helps to work as an aggregator to control number of dispersed EVs in a particular region and manage the energy demand in that area to prevent overloading in existing power system. The first model proves that charging was carried out at hours when the price of electricity is low and discharging is done when price of electricity is high. So by controlling this charging/Discharging Patterns it will be easy to integrate with the existing system. By V2G transactions, EV owner can make revenue during parking hours. In this model, plug availability is not the factor as we have considered a workplace, so depending upon the number of employees it is considered, that many plugs are available. The results also show that if profit is the only goal of the parking lot or charging station then the net power taken from the grid is greatly reduced during peak load hours.

After incorporating the power optimization algorithm as a second model, optimal charging and discharging power is found out which prevents the distributed network to get damage as power flow through branch must be within permissible limits. The reduction of power fluctuations is the result of power optimization strategy. So replacing the price curves with power demand curves to reduce peak power, different grid issues can be solved. So after PEV integration the cases of overloading are reduced, power fluctuations are reduced and thus load curve becomes smoother by incorporating these optimization strategies. The power optimization strategy maintains balance between PEV user profit and stable operation of grid. Thus on aggregate this proposed algorithm not only tries to flat the load profile but also helps the EV owner to generate revenue leading to more and more individuals shift towards combustion less energy and thus helps to control the pollution.

6.2 Future Scope:

The above discussions show the preliminary charging station or parking lot power transactions scheduling techniques. After exploring these power optimization and profit maximization techniques, different problems can also be accounted which are as follows

- By including the power factor control strategy with the existing profit maximization strategy, expands our hands in the markets of regulation and spinning reserves.
- Scheduling of different power sources such as large scale wind farms and the existing thermal plants, with the fleet of electric vehicle storage increases the profit to a great extent.
- By improving the methodology towards the multi bus distribution system which is more practical, and carry out simulations in line with that increases the credibility of results.
- By including the battery degradation profile, one can limit the V2G and G2V transactions and thus increases the life span of battery.

REFERENCES

1. Line Fiskum Hexeberg, “Strategies of smart charging of Electrical Vehicles”, Master thesis first edition, Sweden, 2014.

2. C. Hutson, G.K. Venayagamoorthy, and A.K. Corzine, “Intelligent scheduling of hybrid and electric vehicle storage capacity in a parking lot for profit maximization in grid power transactions,” *IEEE Energy 2030 Conference*, pp. 1-8, Atlanta, GA, 2008.

3. Masoud Honarmand, Alireza Zakariazadeh, Shahram Jadid “Optimal scheduling of electric vehicles in an intelligent parking lot considering vehicle-to-grid concept and battery condition” *Energy Convers Manage, Volume 65*, 1 February 2014, Pages 572-579

4. James Munster-Swendsen, “Optimal system architecture for implementation of Electrical Vehicles on Bornholm”, Master thesis first edition, Denmark, 2012.

5. W. Kempton, J. Tomić, “Vehicle-to-grid power fundamentals: Calculating capacity and net revenue,” *Journal of Power Sources, Volume* 166 Issue 2, 15 April 2007, Pages 549-566.

6. R. C. Eberhart and J. Kennedy, “A new optimizer using particles swarm theory,” *Sixth International Symposium on Micro Machine and Human Science,* pages 39-43, Nagoya, Japan, 1995.

7. del Valle Y, Venayagamoorthy GK, Mohagheghi S, Hernandex JC, Harley RG, “Particle Swarm Optimization: Basic Concepts, Variants and Applications in Power Systems”, *IEEE Transactions on Evolutionary Computation,* Vol. 12, Issue 2, April 2008, pp. 171-195.

8. J. Kennedy and R.C. Eberhart, “A discrete binary version of the particle swarm algorithm,” *IEEE Conference on Systems, Man and Cybernetics,* pages 4104-4108, Orlando FL, 1997.

9. Khanesar, M.A.; Teshnehlam, M.; Shoorehdeli, M.A.; “A novel binary particle swarm optimization,” *Control & Automation, 2007. MED ’07. Mediterranean Conference on,*27-29 June 2007 Page(s): 1-6.

10. Lopes JAP, Soares FJ, Almeida PMR. Integration of electric vehicles in the electric power system. In: Proceedings of IEEE, vol. 99; 2011. pp. 168e83.

11. Zhang Q, Ishihara NK, Mclellan CB, Tezuka T. Scenario analysis on electricity supply and demand in future electricity system in Japan. *Energy,* Volume 38, Issue 1, February 2012, Pages 376-385

12. W. Zhenpo and L.Peng, “Analysis on storage power of electric vehicle charging station”, in Proc. Asia-Pacific Power Energy Eng. Conf., Chengdu, China, Mar. 2010.

13. M.D. Galus and G. Anderson, “Demand management of grid connected plug-in hybrid electric vehicles (PHEV),” in Proc. IEEE Energy 2030 Conf. Atlanta, GA, Feb, 2008.

14. K.J Dyke, N. Schofield, and M. Bames, “The impact of transport electrification on electrical networks,” IEEE Trans. Ind. Electron, Vol. 57, no. 12, pp. 3917-3926, Dec. 2010.

15. Jasna Tomić, Willett Kempton, “Using fleets of electric-drive vehicles for grid support,” *Journal of Power Sources,* Volume 168, Issue 2, 1 June 2007, Pages 459-468

16. Haiming Fu, Yinghua Han , Jinkuan Wang, and Qiang Zhao, “ Novel optimization of plug-in electric vehicles charging and discharging behaviors in electrical distribution grid”, *Journal of Electrical and Computer Engineering,* Volume 2018, Article ID 5091084

17. M. E. Baran and F. F. Wu, “Network reconfiguration in distribution systems for loss reduction and load balancing,” *IEEE Transactions on Power Delivery*, vol. 4, no. 2, pp. 1401–1407, 1989.

APPENDICES

A.1 Swarm Intelligence:

Particle Swarm Optimization (PSO) and its many variants have been used extensively in power system studies. PSO is a form of nature inspired computing that draws its inspiration from the flocking behaviour of birds [6], [7]. Any problem which can have a mathematical formulation has variables which are bound by a set of constraints. As a result of which this problem will have a well-defined solution space. PSO involves the releasing of a number of particles that search the given solution space for the global optimum value of the function. One of the factors that has led to widespread acceptance of PSO as the algorithm of choice for optimization is because the computational times remain low even though the dimensionality of the problem increases. This is due to the fact that, PSO is modelled using linear equations. The movement of each particle naturally evolves to an optimal or near-optimal solution. PSO is not largely affected by the size and nonlinearity of the problem, and can converge to the optimal solution in many problems where most analytical methods fail to converge.

The velocity of the particles is updated according to the following expression:

$$V_{ij}(n) = w{*}V_{ij}(n-1) + c_1 * r_1 * (P_{Best}(n) - X_{ij}(n-1)) + c_2 * r_2 * (G_{best}(n) - X_{ij}(n-1)) \quad (1)$$

The position of the particles is updated according to the following expression:

$$X_{ij}(n) = X_{ij}(n-1) + V_{ij}(n) \quad (2)$$

Table A.1: PSO Parameters definition

Symbol	**Definition**
V_{ij}	Initial velocity
w	Inertia weight
c_1	Cognitive acceleration constant
c_2	Social acceleration constant
i	Particle number
j	Dimension.
r_1	Random number
r_2	Random number
P_{Best}	Personal best
G_{best}	Global best
n	Iteration number
X_{ij}	Position

Table A.1 gives definition of different notations used[8],[9] . The terms c_1 and c_2 are the cognitive acceleration and social acceleration constants respectively. c_1 is a user defined term which helps the particle in accelerating towards the position of P_{Best}.Essentially, it scales r_1 and helps in storing the P_{Best} position. Similarly, c_2 is a user defined term which helps the particle in accelerating towards the position of G_{best}. Just like c_1, c_2 helps in scaling *r2* and in this case it helps in storing the G_{best} position

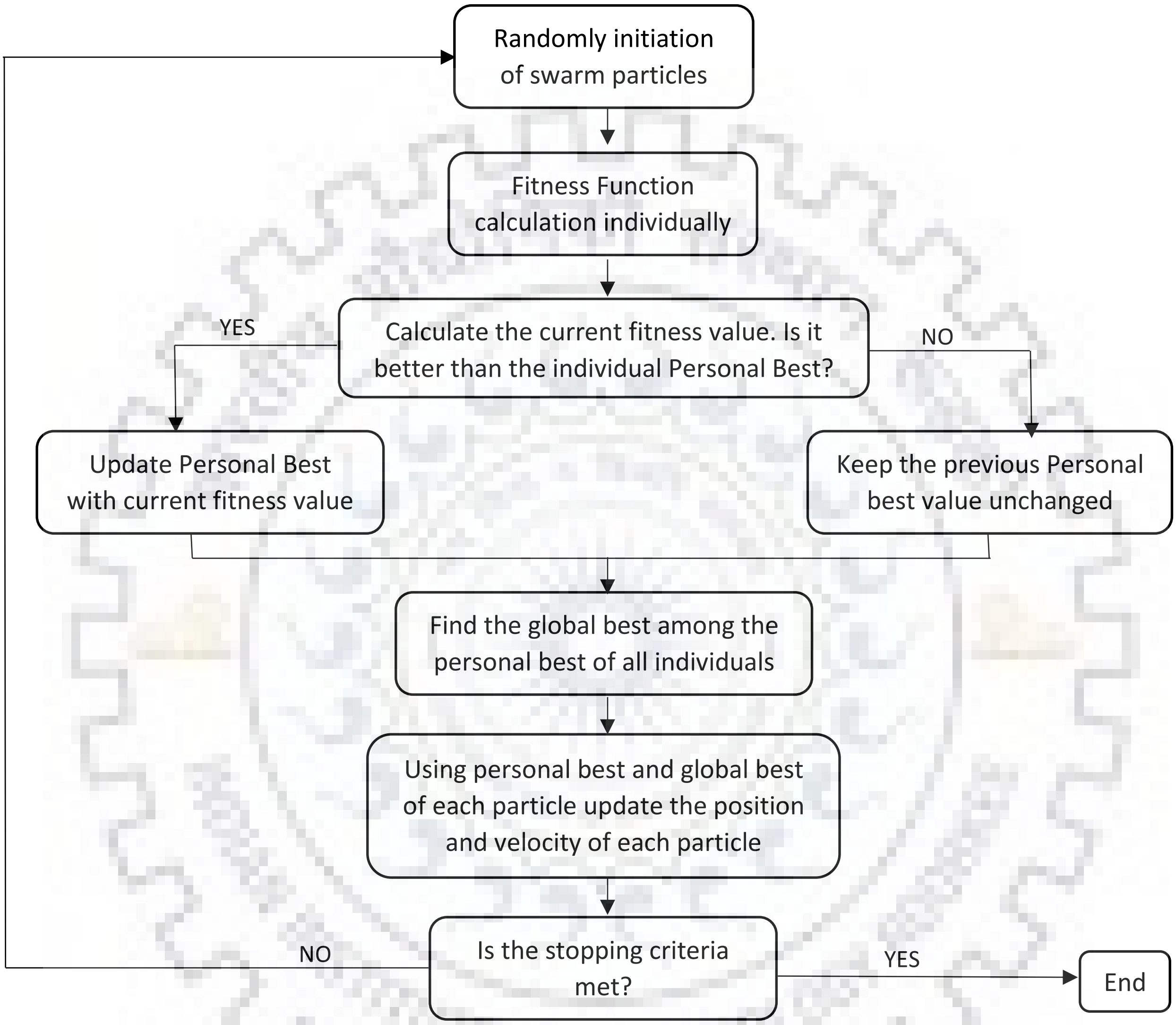


Fig A.1: Flowchart of PSO algorithm

PSO algorithm [2] as represented in fig A.1 follows like:

1. Initialize a population of particles, each representing a possible solution, by assigning random solutions within the given solution space to the problem's variables.
2. Evaluate fitness function assigned to the problem. In this application equation (5) is used with better solutions having a higher result when the fitness function is evaluated.
3. For each particle, compare the fitness at the current iteration with the particle's best previous fitness. The best previous solution for a particle is known as its personal best or P_{Best} solution.
4. Select the best solution of all the P_{Best} solutions to be the global best or G_{best} solution.
5. Update of every particle velocity using (1) and position using (2).
6. Repeat steps 2-5 until a global solution is found within a predefined number of iterations.

A.2 Data set for different charging strategies:

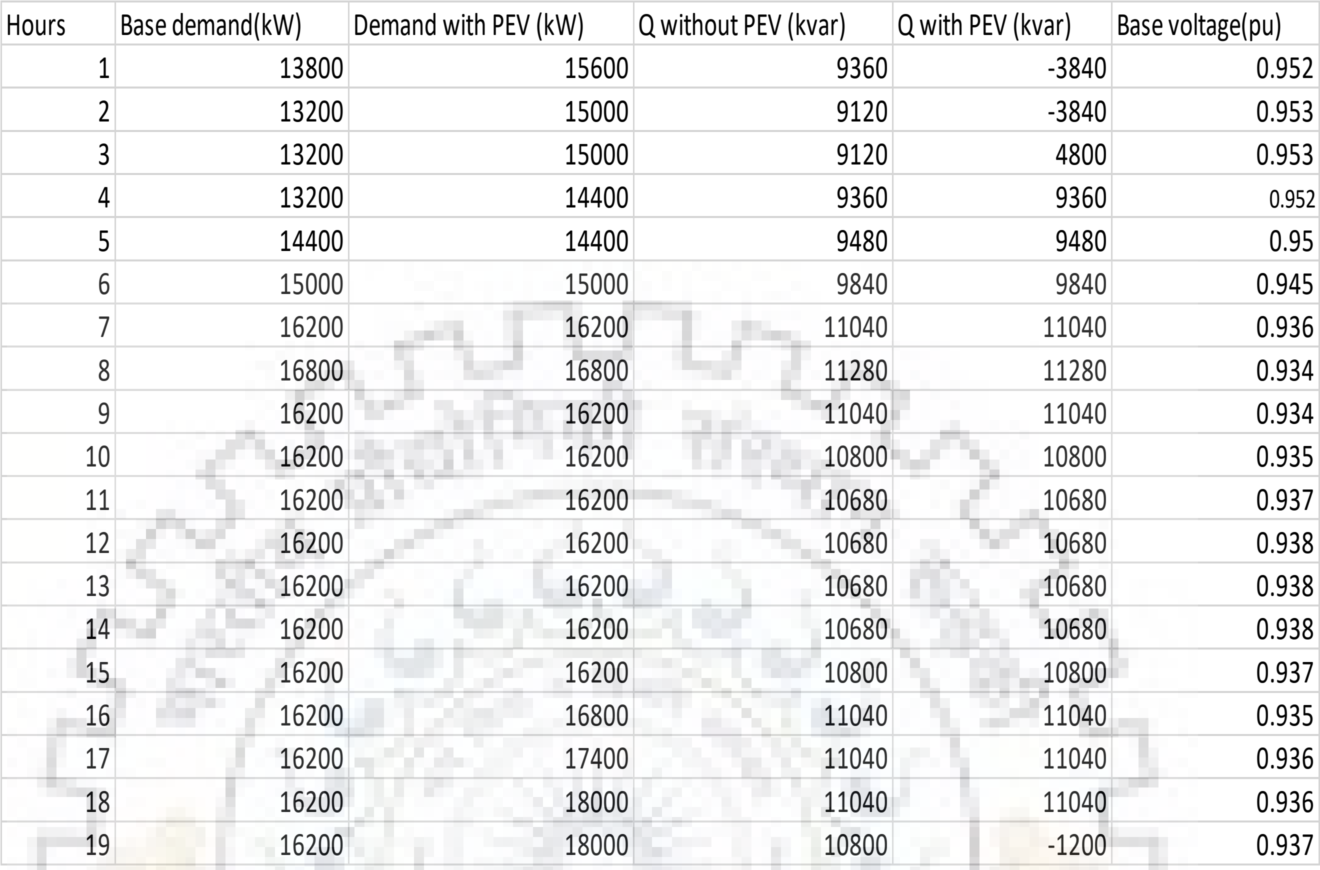
Table A.2.1: Data set for dumb charging scenario

Hours	Base demand(kW)	Demand with PEV (kW)	Base voltage(pu)	Voltage with PEV(pu)
1	14400	14400	0.952	0.952
2	13800	13800	0.953	0.953
3	13800	13800	0.953	0.953
4	14400	14400	0.952	0.952
5	15000	15000	0.95	0.95
6	15000	15000	0.945	0.945
7	16200	16200	0.936	0.936
8	16800	16800	0.935	0.935
9	16800	16800	0.935	0.935
10	16200	16800	0.936	0.936
11	15840	15840	0.938	0.938
12	15840	16800	0.938	0.937
13	15840	16800	0.939	0.937
14	15840	16800	0.939	0.939
15	16200	16800	0.939	0.935
16	16800	17400	0.936	0.934
17	17400	18600	0.935	0.93
18	16800	24000	0.936	0.915
19	16800	25200	0.937	0.915
20	16200	23400	0.938	0.918
21	15840	16800	0.94	0.938
22	15600	16200	0.944	0.941
23	15000	15000	0.949	0.949
24	14400	14400	0.951	0.951

Table A.2.2: Data set for Profit maximization scenario

Hours	Base demand(kW)	Demand with PEV (kW)	Base voltage(pu)	Voltage with PEV(pu)
1	14400	20400	0.952	0.936
2	14160	21600	0.953	0.932
3	14160	21600	0.953	0.932
4	14400	21000	0.952	0.934
5	14640	17400	0.95	0.942
6	15000	15000	0.945	0.945
7	16200	15000	0.936	0.94
8	16800	15000	0.934	0.939
9	16200	15000	0.934	0.939
10	16200	16200	0.935	0.935
11	15600	18000	0.937	0.934
12	15600	16200	0.938	0.936
13	15600	15000	0.938	0.94
14	15600	14400	0.938	0.941
15	16200	14400	0.937	0.941
16	16800	14160	0.935	0.941
17	16800	13800	0.936	0.942
18	16200	13800	0.936	0.942
19	16200	14400	0.937	0.94
20	15240	15240	0.938	0.938
21	15000	18000	0.94	0.936
22	15000	17760	0.944	0.938
23	14640	14640	0.949	0.948
24	14520	18000	0.956	0.94

Table A.2.3: Data set for Power Factor control scenario



Hours	Base demand(kW)	Demand with PEV (kW)	Q without PEV (kvar)	Q with PEV (kvar)	Base voltage(pu)
1	13800	15600	9360	-3840	0.952
2	13200	15000	9120	-3840	0.953
3	13200	15000	9120	4800	0.953
4	13200	14400	9360	9360	0.952
5	14400	14400	9480	9480	0.95
6	15000	15000	9840	9840	0.945
7	16200	16200	11040	11040	0.936
8	16800	16800	11280	11280	0.934
9	16200	16200	11040	11040	0.934
10	16200	16200	10800	10800	0.935
11	16200	16200	10680	10680	0.937
12	16200	16200	10680	10680	0.938
13	16200	16200	10680	10680	0.938
14	16200	16200	10680	10680	0.938
15	16200	16200	10800	10800	0.937
16	16200	16800	11040	11040	0.935
17	16200	17400	11040	11040	0.936
18	16200	18000	11040	11040	0.936
19	16200	18000	10800	-1200	0.937