Direct Load Control Decision Model applied to Electric Vehicle Charging Points

V UCM Modeling Week

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1 Introduction

Electric vehicles are becoming an alternative to combustion engines due to their low emissions, high energy efficiency and competitive autonomy range.The two main current available technologies are Electric Vehicles (EV) and Plug-in Hybrid Electric Vehicle (PHEV). The EV uses one or more electric motors or traction motors for propulsion, whereas a PHEV shares the characteristics of both a conventional hybrid electric vehicle, having an electric motor and an internal combustion engine (ICE); and of an all-electric vehicle
In 2009, the Council of Ministers gave its approval to the signing of three Collaboration Agreements in order to implement an operational start-up of a pilot network of public electric vehicle recharging stations, within the framework of a pilot project called MOVELE.
One of project MOVELE's aim is to activate stimulus measures among the local authorities concerned to enable the creation of a network of supply points located on streets and in public car parks, as a step towards a total of 2000 electric vehicles being driven on the roads within two years.
In the figure 1 we can observe the increasing of the number of the vehicles fueled alternatively, and how they are becoming more important.

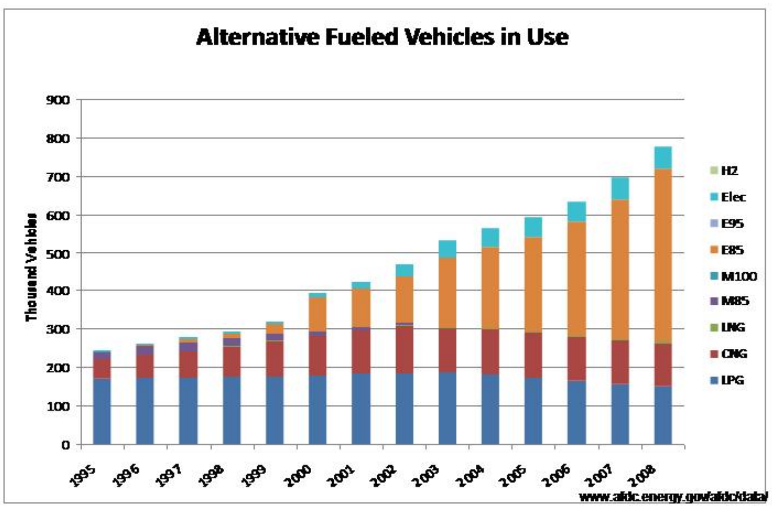


Figure 1: Number of Alternative Fueled Vehicles in Use

Electric vehicles are propelled by an electric motor (or motors) powered by rechargable battery packs. Electric motors have several advantages over internal combustion engines (ICEs):

- Energy efficient: Electric motors convert 75% of the chemical energy from the batteries to power the wheels, and internal combustion engines (ICEs) only convert 20% of the energy stored in gasoline.

- Environmentally friendly: Electric vehicles s emit no tailpipe pollutants, although the power plant producing the electricity may emit them. Electricity from nuclear, hydro, solar or wind powered plants causes no air pollutants.

- Performance benefits: Electric motors provide quiet, smooth operation and stronger acceleration and require less maintenance than ICEs.

- Reduce energy dependance: Electricity is a domestic energy source.

Electric vehicles face also significant battery-related challenges:

- Driving range: Most EV'S can only go about 100-200 milles before recharging. However,gasoline vehicles can go over 300 milles before refueling.

- Recharge time: Fully recharing the battery pack can take 4 to 8 hours.

- Battery cost: The large battery packs are expensive and may need to be replaced one or more times.

- Bulk and weight: Battery packs are heavy and take up considerable vehicle space.

Current available electric vehicles have a shorter range per charge than most conventional vehicles have per tank of gas. EV manufacturers typically target a minimum range of 100 milles (160 km aprox.). For instance, according to the U.S. department of Transportation Federal Highway Administration, 100 milles is sufficient for more than 90% of all household vehicle trips in the United States. For longer trips, it is necessary to charge the vehicle or swap the battery en route.
The public charging infrastructure should consist of charging locations where vehicle owners are highly concentrated:

- shopping centers
- city parking lots and garages
- airports
- hotels
- government offices
- other businesses

Widespread public charging infrastructure will help facilitate the penetration of all-electric vehicles and plug-in hybrid electric vehicles and help address consumer 'range anxiety' for those vehicles with limited range.

2 Considered model

In this section, we present the model that we used to try to design the electrical vehicle charging policies.
The main assumptions defining the model were:

- We used three EV models with different capacities and charging rates. The Nissan-Leaf with a Capacity of 24Kwh and a Charging Rate of 3.3 KWh, Renault Fluence ZE (Capacity: 20 KWh, Charging Rate: 3.3 KW), and the Mitsubishi iMiEV (Capacity: 16 KWh, Charging Rate: 2.3 KW).
- The electricity prices were taken from real dates in April 2010.
- We assume an initial level of charge integer, and a capacity integer too.
- Time unit is one hour.
- The arrival times and living times are integer.
- Vehicles always want to leave the garage at full energy capacity.
- To avoid battery damage a minimun level of energy storage should be achieved without discharging.

2.1 First Model

2.1.1 Sets

$$
\begin{aligned}
i &= 1, ..., n \qquad (\#\text{ cars}) \\
j &= 0, ..., 48 \qquad (\text{hours})
\end{aligned} \tag{1}
$$

2.1.2 Input

In our first model, the parameters are:

- $arrive_i$ arrival time of EV i
- $leave_i$ leaving time of EV i
- $level_i$ initial power level of EV i
- $demand_i$ power demand of EV i
- $capacity_i$ initial power level of EV i
- $price_j$ price of electricity at time j
- L power limit of the garage (KW)
- M minimum level of recharge rate (KW)
- CR_i maximum recharging rate of EV i (KWh)
- GR maximum recharging rate of the garage (KWh)

2.1.3 Variables

$$
\begin{aligned}
DNS1_i &= \text{Demand not satisfied counting from 70\% of capacity i} \\
DNS2_i &= \text{Demand not satisfied until 70\% of capacity i} \\
P_{ij} &= \text{Power supplied to i in hour j} \\
\delta_{ij} &= \begin{cases} 1, & \text{if car i charges during hour j,} \\ 0, & \text{otherwise} \end{cases} \\
\alpha_{ij} &= \begin{cases} 1, & \text{if car i starts charge at hour j+1,} \\ 0, & \text{otherwise} \end{cases}
\end{aligned} \tag{2}
$$

2.1.4 Constraints

- Don't exced the limit of power provided by the garage:
  $\sum_{i=1}^{n} P_{ij} \leq L \qquad \forall j$

- Don't charge before the car arrives:
  $\sum_{j=1}^{arrive_i} \delta_{ij} = 0 \qquad \forall i$

- Don't charge once the car has left:
  $\sum_{j=leave_i}^{48} \delta_{ij} = 0 \qquad \forall i$

- The power provided has to meet both garage and car specifications:
  $P_{ij} \leq CR_i^* \cdot \delta_{ij} \qquad \forall i, j$where $CR_i^* = min\{CR_i, GR\}$

- State of charge car i at hour j:
  $SOC_{ij} = initial\_level_i + \sum_{k=0}^{j} P_{ij} \qquad \forall i, j$

- Minimum power supplied:
  $P_{ij} \geq \delta_{ij} \cdot M \qquad \forall i, j$

- Demand should be equal supplied plus not satisfied demand:
  $demand_i = DNS1_i + DNS2_i + \sum_{j=1}^{48} P_{ij} \qquad \forall i$

- Number of times i starts charging:
  $\delta_{ij+1} - \delta_{ij} \leq \alpha_{ij} \qquad \forall i, j$

- At most each car is started once:
  $\sum_{j=1}^{48} \alpha_{ij} \leq 1 \qquad \forall i$

- Demand (below 70% not satisfied)
  $DNS2_i = 0.7 \cdot capacity_i - min\{0.7 \cdot capacity_i, supplied_i + inicial\_level_i\}$
  $\forall i$

- We divide the total amount of demand not satisfied into two parts
  $DNS1_i \leq 0.3 \cdot capacity_i \qquad \forall i$

- Demand not satisfied below 70%
  $DNS2_i \leq 0.7 \cdot capacity_i \qquad \forall i$

- $\delta_{ij}, \alpha_{ij} \in 0, 1$

- $supplied_i, DNS1_i, DNS2_i, P_{ij} \in \Re$

2.1.5 Objective function

We want to minimize the cost for the garage penalizing the demand not satisfied

$$min \sum_{i=1}^{n} \sum_{j=1}^{48} P_{ij} \cdot price_j + p_1 * \sum_{i=1}^{n} DNS1_i + p_2 * \sum_{i=1}^{n} DNS2_i$$

2.2 Second Model

In our second model, we will assume that sell energy is possible in the process known like Vehicle to Grid (V2G).
Vehicle to grid (V2G) describes a system in which plug-in electric vehicles, such as electric cars and plug-in hybrids communicate with the power grid to sell demand response services by either delivering electricity into the grid or by throttling their charging rate. Since most vehicles are parked an average of 95 percent of the time, their batteries could be used to let electricity flow from their car to the power lines and back, with a value to the utilities. It can enable utilities new ways to keep voltage and frequency stable and provide reserves to meet sudden demands for power. Since demand can be measured locally by a simple frequency measurement, dynamic load leveling can be provided as needed.
When the electric utility would like to buy power from the V2G network, it holds an auction. It is what we call 'carbitrage', (This is the fusion of 'car' and 'arbitrage'). The car owners are able to define the parameters under which they will sell energy from thei battery pack. Many factors would be considered when setting minimum sale price including the cost of the secondary fuel in a PHEV and battery cycle wear. When this minimum price is satisfied, it is deemed as meeting carbitrage.

2.2.1 Variables

With the same parameters and sets than in the first model, we can define the new variables:

$$\begin{aligned} Q_{ij} &= \text{Power sold to distributor from car i at hour j} \\ \eta_{ij} &= \begin{cases} 1, & \text{if car i discharges during hour j,} \\ 0, & \text{otherwise} \end{cases} \qquad (3) \\ SOC_{ij} &= \text{State of charge car i at hour j} \\ FLAG_{ij} &= \text{Defines either you are over(1) or below(0) 70\%} \end{aligned}$$

2.2.2 Constraints

- Limit of the distributor:
  $-L \leq \sum_{i=1}^{n} (P_{ij} - Q_{ij}) \leq L \qquad \forall j$

- Minimum power supplied:
  $P_{ij} \geq \delta_{ij} \cdot M \qquad \forall i, j$

- Minimum power the garage sells:
  $Q_{ij} \geq \eta_{ij} \cdot M \qquad \forall i, j$

- Demand should be equal to the supplied plus the not satisfied demand :
$demand_i = DNS1_i + DNS2_i + \sum_{j=1}^{48} P_{ij} + \sum_{j=1}^{48} Q_{ij} \qquad \forall i$

- You can't charge and discharge at the same time
$\delta_{ij} - \eta_{ij} \leq 1 \qquad \forall i, j$

- State of charge car i at hour j:
$SOC_{ij} = initial\_level_i + \sum_{k=0}^{j} P_{ij} - \sum_{k=0}^{j} Q_{ij} \qquad \forall i, j$

- Variable FLAG defines either you are over or below 70%:
$SOC_{ij} \geq 0.7 \cdot capacity_i \cdot FLAG_{ij} \qquad \forall i, j$
$SOC_{ij} \leq 0.7 \cdot capacity_i \, (1 - FLAG_{ij} + capacity_i \cdot FLAG_{ij}) \qquad \forall i, j$

- Battery can't stop charging before it reaches the 70% level:
$\delta_{ij+1} - \delta_{ij} \leq \alpha_{ij} + FLAG_{ij} \qquad \forall i, j$

- Battery can't be discharged when level is below 70%:
$\eta_{ij+1} \leq FLAG_{ij} \qquad \forall i, j$

- Below 70% level, battery can't only start charging once:
$\sum_{j=1}^{48} \alpha_{ij} \leq 1 \qquad \forall i$

- $\delta_{ij}, \alpha_{ij}, \eta_{ij}, FLAG_{ij} \in 0, 1$

- $SOC_{ij}, supplied_i, DNS1_i, DNS2_i, P_{ij}, Q_{ij} \in \Re$

2.2.3 Objective function

We want to minimize the cost for the garage penalizing the demand not satisfied

$$min \sum_{i=1}^{n} \sum_{j=1}^{48} P_{ij} \cdot price_j + p_1 * \sum_{i=1}^{n} DNS1_i + p_2 * \sum_{i=1}^{n} DNS2_i - \sum_{i=1}^{n} \sum_{j=1}^{48} Q_{ij} \cdot price_j$$

2.3 Third Model

2.3.1 Variables

We can define the new variables:

$$
\begin{aligned}
DNS1_i &= \text{Demand not satisfied counting from 70\% of capacity i} \\
DNS2_i &= \text{Demand not satisfied until 70\% of capacity i} \\
P_{ij} &= \text{Power supplied to i in hour j} \\
\delta_{ij} &= \begin{cases} 1, & \text{if car i charges during hour j,} \\ 0, & \text{otherwise} \end{cases} \\
Q_{ij} &= \text{Power sold to distributor from car i at hour j} \\
\eta_{ij} &= \begin{cases} 1, & \text{if car i discharges during hour j,} \\ 0, & \text{otherwise} \end{cases} \\
SOC_{ij} &= \text{State of charge car i at hour j} \\
FLAG_{ij} &= \text{Defines either you are over (1) or below (0) 70\%} \\
M_{ij} &= \text{Power given by car i to car j} \\
N_{ij} &= \text{Power recived by car i from car j}
\end{aligned}
\tag{4}
$$

2.3.2 Constraints

- Limit of the distributor:
  $-L \leq \sum_{i=1}^{n} (P_{ij} - Q_{ij}) \leq L \qquad \forall j$

- Don't charge or discharge before the car arrives:
  $\sum_{j=1}^{arrive_i} \delta_{ij} = 0,\ \sum_{j=1}^{arrive_i} \eta_{ij} = 0 \qquad \forall i$

- Don't charge or discharge after the car has left:
  $\sum_{j=leave_i}^{48} \delta_{ij} = 0,\ \sum_{j=leave_i}^{48} \eta_{ij} = 0 \qquad \forall i$

- The power provided has to meet both garage and car specifications:
  $P_{ij} + M_{ij} \leq CR_i^* \cdot \delta_{ij} \qquad \forall i, j \text{where } CR_i^* = min\{CR_i, GR\}$

- Power sold to distributor has to meet both garage and car specification:
  $Q_{ij} + N_{ij} \leq CR_i^* \cdot \eta_{ij} \qquad \forall i, j \text{where } CR_i^* = min\{CR_i, GR\}$

- Minimum power supplied:
  $P_{ij} + M_{ij} \geq \delta_{ij} \cdot M \qquad \forall i, j$

- Minimum power the garage sells:
  $Q_{ij} + N_{ij} \geq \eta_{ij} \cdot M \qquad \forall i, j$

- The amount of energy given by the cars to others, must be the same that the amount of energy received:
  $\sum_{k=0}^{j}(M_{ij} - N_{ij}) = 0 \qquad \forall i, j$

- Demand should be equal to the supplied plus the not satisfied demand :
  $demand_i = DNS1_i + DNS2_i + \sum_{j=1}^{48} P_{ij} + \sum_{j=1}^{48} Q_{ij} + \sum_{k=0}^{j} M_{ij} + \sum_{k=0}^{j} N_{ij} \qquad \forall i$

- DNS1 is the demand over 70% not satisfied
  $DNS1_i \leq 0.3 \cdot capacity_i \qquad \forall i$

- You can't charge and discharge at the same time
  $\delta_{ij} - \eta_{ij} \leq 1 \qquad \forall i, j$

- State of charge car i at hour j:
  $SOC_{ij} = initial\_level_i + \sum_{k=0}^{j} P_{ij} - \sum_{k=0}^{j} Q_{ij} \qquad \forall i, j$

- The battery can't get below 0%:
  $SOC_{ij} \geq 0 \qquad \forall i, j$

- Variable FLAG defines either you are over or below 70%:
  $SOC_{ij} \geq 0.7 \cdot capacity_i \cdot FLAG_{ij} \qquad \forall i, j$
  $SOC_{ij} \leq 0.7 \cdot capacity_i \, (1 - FLAG_{ij} + capacity_i \cdot FLAG_{ij}) \qquad \forall i, j$

- Don't allowed to go below 70% once you reached it:
$FLAG_{ij} - FLAG_{ij} \geq 0 \qquad \forall i$

- Battery can't stop charging before it reaches the 70% level:
$\delta_{ij+1} - \delta_{ij} \leq \alpha_{ij} + FLAG_{ij} \qquad \forall i, j$

- Battery can't be discharged when level is below 70%:
$\eta_{ij+1} \leq FLAG_{ij} \qquad \forall i, j$

- Below 70% level, battery can't only start charging once:
$\sum_{j=1}^{48} \alpha_{ij} \leq 1 \qquad \forall i$

- $\delta_{ij}, \alpha_{ij}, \eta_{ij}, FLAG_{ij} \in 0, 1$

- $SOC_{ij}, supplied_i, DNS1_i, DNS2_i, P_{ij}, Q_{ij} \in \Re$

2.3.3 Objective function

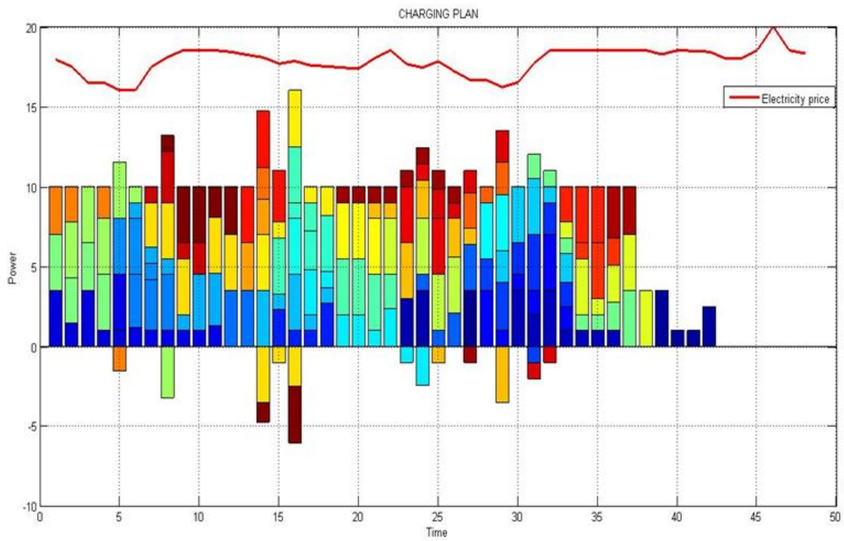
We want to minimize the cost for the garage penalizing the demand not satisfied

$$min \sum_{i=1}^{n} \sum_{j=1}^{48} P_{ij} \cdot price_j + p_1 * \sum_{i=1}^{n} DNS1_i + p_2 * \sum_{i=1}^{n} DNS2_i - \sum_{i=1}^{n} \sum_{j=1}^{48} Q_{ij} \cdot price_j$$

3 Results

Our results are based in the second model considered; in which we are also allowed to sell energy to the grid. In the following pictures we can observe different simulations depending of the grid limit with 50 cars. In the upper picture, each car is represented by a different colour, and we can observe when a car is buying energy (positive values of power), and when they are selling it (negative values od energy). And in the lower one, we represente the $arrival_time$ and the $leaving_time$ of each car related with the size of the rectangle. Green and blue, show us when the cars are charging; and the light green and light blue represent a car selling (discharging) energy.

Where we assume a lower grid limit of 10KW, figure (2), we can observe that we are almost charging during the whole 48 hours, and independently of the price. This is because the most impoprtant thing for our car is to be charged when they have to leave. However, if we assume a limit of 15KW, figures (4), there are moments (when the electricy price is higher), where the cars sell more energy, because when the limit increases there grid limit to charge more cars with a electricity price lower.



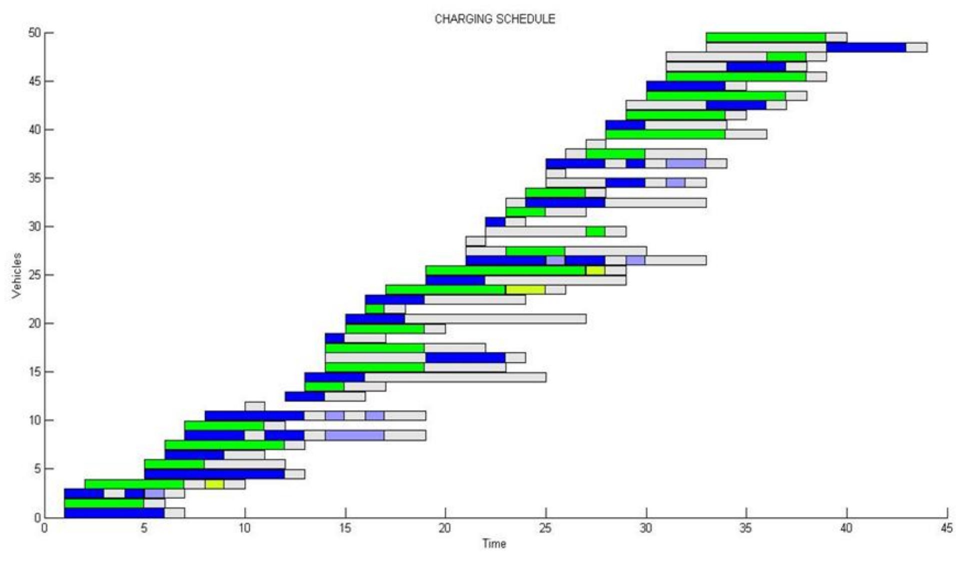


Figure 2: Charging plan and schedule with grid limit equal to 10 KW

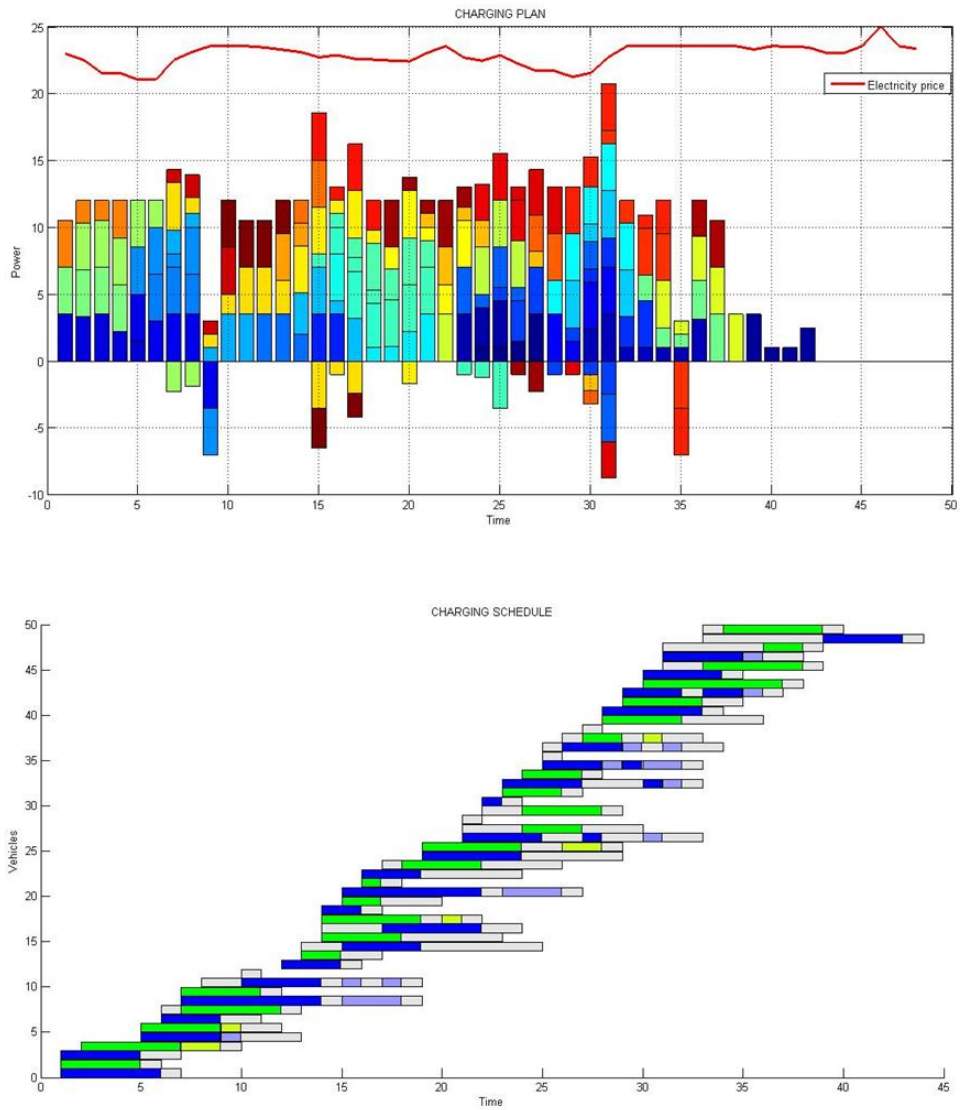
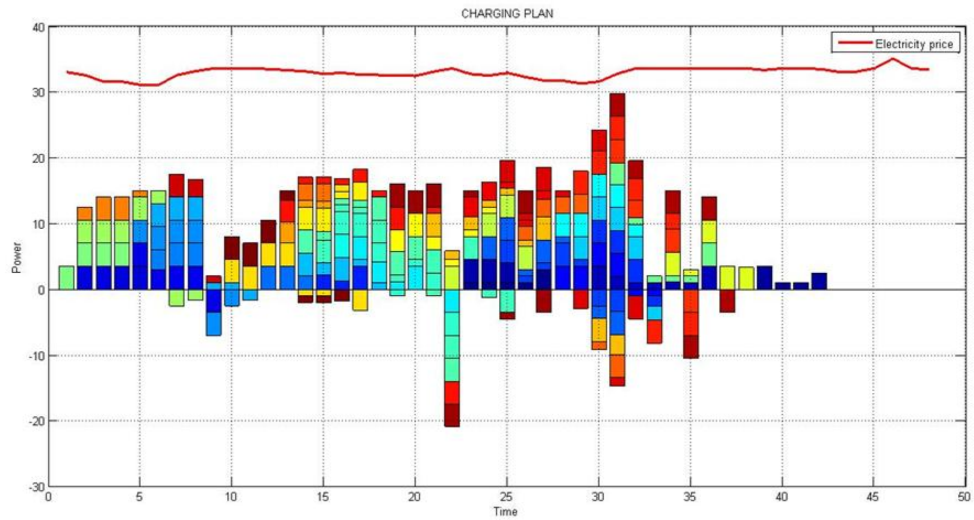


Figure 3: Charging plan and schedule with grid limit equal to 12 KW



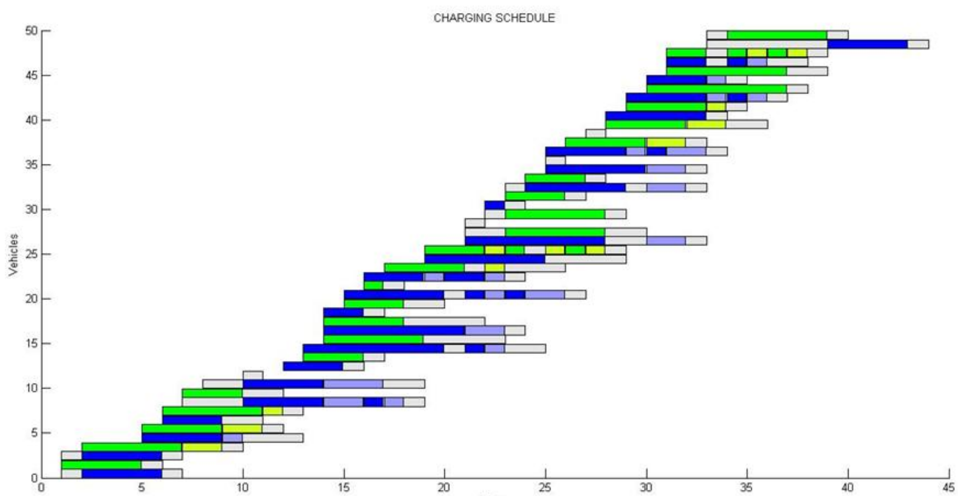


Figure 4: Charging plan and schedule with grid limit equal to 15 KW

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