# Optimal Scheduling of Plug-in Electric Vehicles in Distribution Systems Including PV, Wind and Hydropower Generation

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***Abstract*— Integration of Plug-in Electric Vehicles (PEVs) and renewables pose substantial challenges on electricity distribution networks. The focus of this paper is to investigate the impact of large-scale PEVs penetration combined with the integrating of variable Renewable Energy Resources, e.g., wind, hydropower and PVs on distribution network. In this respect, simulation analysis on an existing low voltage local power system is conducted. We propose an ACOPF algorithm over a time horizon of several successive hours. Controlling voltage fluctuations in the safe bound, optimal charging of PEVs, covering the total energy consumption of users, and forecast generation of renewables are considered in an optimization framework. Simulation results show our proposed algorithm saves 2.4% total cost in compared with a dumb-charging scenario.**

**Keywords- ACOPF, Plug-in Electric Vehicles, Voltage quality, PV, Wind Power Plants, Optimal Charging**

## I. NOMENCLATURE

| | |
|---|---|
| $i$ | Bus index |
| $t$ | Time index |
| $P_G$ | Active power flow from/to the upstream network. |
| $N$ | Total number of buses in the network. |
| $T, \Delta t$ | Total number of discrete intervals per planning horizon and the time step. |
| $\gamma_{spot}(t)$ | Electricity price at the wholesale market (spot price) |
| $P_{LD,i}(t)$, $Q_{LD,i}(t)$ | Active and reactive power demand |
| $P_{DG,i}(t)$, $Q_{DG,i}(t)$ | Active and reactive power production from the distributed generator. |
| $P_{SCh,i}(t), P_{SDch,i}(t)$, | Charging and discharging power of a PEV. |
| $Q_{\mathrm{ST},i}(t)$ | Reactive power supplied from the battery energy storage. |
| $V_i(t), \delta_i(t)$ | Voltage amplitude and the angle. |
| $Y_{ij}(t), \theta_{i,j}(t)$ | Network admittance amplitude and angle. |
| $I_{line,rated}$ | Rated current capacity of the lines. |
| $Q_{DG,i}^{\min}, Q_{DG,i}^{\max}$ | Minimum and maximum limit of the reactive power capability of the DG. |
| $V_{\min}, V_{\max}$ | Minimum and maximum limit of the voltage amplitude. |
| $P_{SCh,i}^{\max}, P_{SDch,i}^{\max}$ | Rated charging and discharging capacity of a PEV. |
| $SOC_i(t)$ | State of charge of PEV. |
| $SOC_i^{\min}, SOC_i^{\max}$ | Minimum and maximum limit of the SOC. |
| $E_{ST,i}(t)$ | Energy stored in the PEV at time step $t$. |
| $E_{ST,i}^{\max}$ | Rated energy capacity of the PEV. |
| $\eta_{chrg,i}, \eta_{dischrg,i}$ | Charging and discharging capacity of the PEV. |

## II. INTRODUCTION

The introduction of incentive schemes for promoting electric vehicles users accelerated the plug-in electric vehicles (PEV) adoption in Norway. All electric vehicles in Norway are exempt from the value added tax and purchase tax. Moreover, they are exempt from road tolls and get free parking in public parking spaces, free battery charging at publicly funded charging stations, and are allowed to use bus and collective traffic lanes [1]. By 2016, Norway is the largest user of electric vehicles per capita in the world. PEVs are free of air pollutant emissions, hence environmentally friendly, particularly in Norway because 98% of the electricity production is from the hydropower. Although, PEVs help to reduce the greenhouse gas emissions, high penetration of PEVs may result in significant technical issues in distribution grids if charging is not properly coordinated. Uncoordinated charging of PEVs can overload the transformers, increase losses, cause under-voltage problems, and increase harmonic distortion [2], [3], [4]. Therefore, proper coordination of PEVs charging is required in order to utilize the existing infrastructure optimally for PEVs charging without adversely affecting the distribution network. Further, it is important to consider the cost of energy and the production from the distributed generators in the distribution grid for example photovoltaic (PV) systems and small-scale wind turbines. Charging the PEVs during low electricity price period is economically attractive for the distribution system operator as well as the PEV owner. Indirectly, that helps the grid to shift the PEV load to the period when the grid is lightly loaded, because the electricity price reflect the heavily loaded and lightly loaded times of the grid. Moreover, it is important to maximally utilize the energy production from the distributed generators in the network.

The optimal power flow has been applied to find an optimal operating of an electric power grid over a certain time horizon provided that both the load and the supply are deterministic. Several methods have been proposed for solving ACOPF problems efficiently [5], [6]. Therefore, this has been effectively applied for distribution system optimization recently. The conventional AC Optimal Power Flow (ACOPF) is a numerical analysis toolbox that can be used to consider system costs, grid limitations and charging coordination of storages. It formulated in 1962 [7] for a basic problem to find a local optimum operating point for power systems. Since that time, many efforts have been made for solution of optimization algorithm more efficiently [8], [9], [10]. They use nonlinear programming (NLP) based methods. The need for optimization of distribution system with wholesale market transactions including distributed energy resources (DER) have been discussed in the literature earlier. [11] indicates the main aspects of DER, and the challenges and potential solutions for implementing Demand Response in smart grid market. Ref. [12] suggests a new algorithm for distribution management system (DMS) that can be applied to active distribution networks and [13] proposes an algorithm for distribution system operation. Several forecasting methods have been proposed that integrates variability and changes in the resources. Reference [14] introduced a method for maximizing the profits for market participants. Reference [15] and [16] discusses a study with mixed integer non-linear programming (MINLP) approach for determining optimal location and number of distributed generators in hybrid electricity market.

In this paper, we present an optimal scheduling of PEVs in a Norwegian distribution grid accommodating significant amount of distributed generators and PEVs. We use ACOPF for finding the optimal charging schedule of the PEVs. The rest of the paper is organized as follows. Section III explains the method and Section IV presents the case study. Results from the simulations are provided in Section V along with discussions. Section VI presents conclusions.

## III. METHOD – AC OPTIMAL POWER FLOW

From the perspective of the distribution system operator, the charging of the PEVs should be coordinated so that the cost of buying electricity from the upstream grid is minimized, while maintaining the quality of supply within the desired range, and loading on the transformers and lines below the ratings. The over-voltage problem is a common problem that has been experienced in residential areas with extensive distributed generators mainly PV [17]. The over-power production from PV system during the daytime when the network is usually lightly loaded causes reverse power flow. This can create over-voltage problems in some nodes in the network. On the other hand, PV generators do not produce power during nights. Usually peak load happen in residential areas around 1800h-2000h. During this period, network is prone to under-voltage problems. Charging the PEVs around this time slot can worsen the under-voltage problems. Therefore, both of these conditions should be taken into consideration when coordinating the charging of PEVs. Moreover, the PEVs should be charged using the production from the distributed generators within the system as much as possible. When there is not enough excess local production within the system, the required energy for charging of PEVs should be imported from the upstream grid. Hence, in order to minimize the cost of imported energy from the grid, we have to charge batteries at the time slots where electricity prices are lowest.

### A. Objective Function

The main objective of the distribution system operator is to minimize the cost of energy taken from the upstream grid over a certain time horizon. Here, we assume that the total load on the grid substation transformer is always higher than the production from the distributed generators in the distribution grid. With this assumption, the distribution system operator always buys energy from the upstream grid for the wholesale market price (spot price). Then the objective function can be written as Eq. (1).

$$\text{Objective function} = \min \sum_{t=1}^{T} \gamma_{spot}(t)\ .\ P_G(t)\ .\ \Delta t \tag{1}$$

where $P_G(t)$ is always positive.

#### 1) AC Power Flow Equations

The Kirchhoff's current low must be satisfied at every bus of the network. This results following AC power flow equations for active and reactive power in Eqs. (2) and (3).

$$\begin{aligned} & P_{DG,i}(t) - P_{LD,i}(t) + P_{SDch,i}(t) - P_{SCh,i}(t) \\ & = \sum_{j=1}^{N} |\mathbf{V}_i(t)|\,|\mathbf{V_j}(t)|\,|\mathbf{Y_{i,j}}(t)| \cos(\delta_j(t) - \delta_i(t) + \theta_{i,j}(t)) \end{aligned} \tag{2}$$

$$\begin{aligned} & Q_{DG,i}(t) - Q_{LD,i}(t) \\ & = -\sum_{j=1}^{N} |\mathbf{V}_i(t)|\,|\mathbf{V_j}(t)|\,|\mathbf{Y_{i,j}}(t)| \sin(\delta_j(t) - \delta_i(t) + \theta_{i,j}(t)) \end{aligned} \tag{3}$$

### B. Distributed Generator Constraints

Distributed PV systems and a wind generator are considered as the available distributed generators in the system. The active power production from these units are un-controllable but deterministic. It is assumed that these units can provide reactive power support when required. The reactive power produced from these units should be within its reactive power capability limits represented by Eq. (4).

$$Q_{DG,i}^{\min} \le Q_{DG,i}(t) \le Q_{DG,i}^{\max} \tag{4}$$

### C. Voltage Constraints

The voltage magnitude at all buses in the network should be maintained within the statutory limits illustrated in Eq. (5).

$$V_{\min} \le V_i(t) \le V_{\max} \tag{5}$$

### D. Line Constraints

The current flow in the lines are limited to their rated currents. This limit is represented in Eq. (6).

$$\left|\mathbf{I}_{\mathbf{line,ij}}(t)\right| \le I_{line,rated}\ , \tag{6}$$

where the line current is given by Eq. (7).

$$\mathbf{I}_{\mathbf{line,ij}}(t) = \frac{\mathbf{V}_i - \mathbf{V}_j}{\mathbf{Y}_{ij}} \tag{7}$$

### *E. Plug-in Electric Vehicles*

The battery energy storage in a PEV has a limited energy capacity and its state of charge (SOC) should be maintained within a certain safety limits in order to prolong the battery lifetime. Moreover, the charging and discharging rate should be kept below the rated charging and discharging capacities of the battery. This introduces the following constraints in to the optimization problem.

$$\begin{gathered} 0 \le P_{SCh,i}(t) \le P_{SCh,i}^{\max} \\ 0 \le P_{SDch,i}(t) \le P_{SDch,i}^{\max} \end{gathered} \tag{8}$$

$$SOC_i^{\min} \le SOC_i(t) \le SOC_i^{\max} \tag{9}$$

The SOC of the battery is given by Eq. (10).

$$SOC_i(t) = \frac{E_{ST,i}(t)}{E_{ST,i}^{\max}}\ , \tag{10}$$

where

$$E_{ST,i}(t) = E_{ST,i}(t-1) + \eta_{chrg,i}\ P_{Sch,i}(t)\ \Delta t - \frac{P_{SDch,i}(t)\ \Delta t}{\eta_{dischg}\ , i} \tag{11}$$

This problem is formulated with a matrix, which includes arrival and departure time of each PEV, to specify variables and equations regarding each PEV separately. The problem is solved using MATLAB, fmincon optimization solver, which uses the Interior point method.

## IV. CASE STUDY

The presented method is applied for scheduling the charging of PEVs in the Norwegian distribution grid, which is located in Steinkjer, Nord Trøndelag. This distribution grid consists of 32 distribution transformers (22 kV/230 V), a small scale hydro power plant with rated capacity 2.4 MW, and 856 customers. This distribution grid is supplied by 25 MVA, 66 kV/22 kV transformer at the grid substation. Fig. 1 illustrates the single-phase layout of the 22 kV network of this grid. In this study, only the LV network supplied by the distribution transformer-DT1 indicated in the figure was modelled in detail to account the voltage variation in the LV side (230 V) of the network. The single phase diagram of this LV network is shown in Fig. 2. The number of customers supplied by this network is 62. The highlighted houses in red in Fig. 2 indicate the critical voltage nodes of the network, which have been identified through AC power flow simulations. The other LV networks were modelled as aggregated loads connected to the secondary side of the transformers. The total number of buses in the resulting network is 147.

We assumed that the distribution grid accommodates significant amount of distributed generators. These distributed generators include, rooftop PV generators and single wind generator. The selected location for the wind generator and its connection to the grid is shown in Fig. 1. The rated capacity of the proposed wind generator is 500 kW. The wind generator is connected to the 22 kV network using 500 kVA, 690 V/22 kV transformer. The power production from the wind generator was estimated using the wind measurement data provided by the utility company Nord-Trøndelag Elektrisitetsverk (NTE). We assumed that 50% of the households have PV systems with rated capacity of 4 kW. The locations of the households having PV systems are randomly chosen. In the other part of the distribution grid, PV production is added as an aggregated production at the LV side of the transformer. The hourly power production from PV systems were estimated using the solar irradiance data at the considered location. The load profiles of the consumers over a year (2012) were obtained from NTE. The day with highest demand (February, 2) was chosen for the simulation.

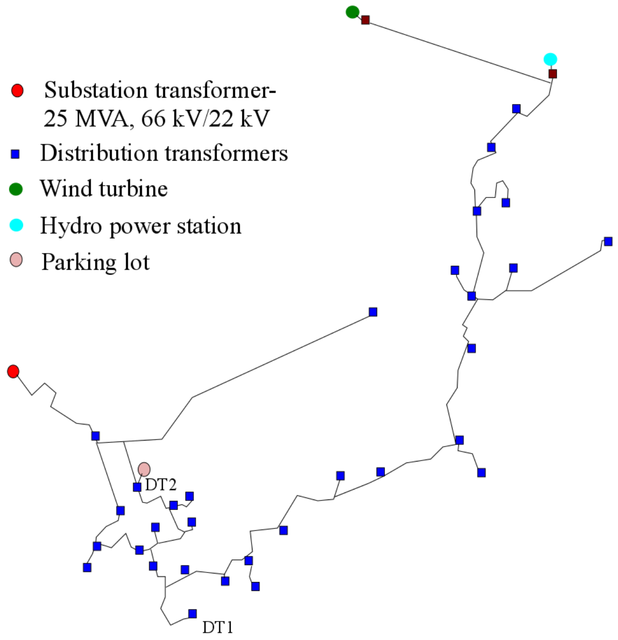

Figure 1. Single-phase layout of the distribution network (22 kV).

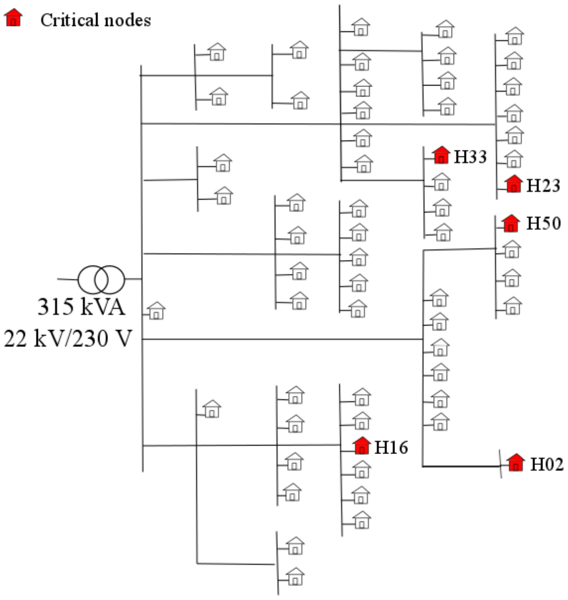

Figure 2. LV network (230 V) supplied by the transformer- DT1.

The average number of vehicles per household in Norway is 1.3 [18]. We assumed a scenario of 50% PEV adoption in Norway. Then the expected number of PEVs in the LV network with 62 households supplied by transformer DT1 is 40. However, the aggregated charging of PEVs connected to the LV networks supplied by the other transformers is not taken into account. We also considered a parking lot located by the transformer DT2 indicated in Fig. 1. The considered number of PEVs connected to the parking lot is 50. The rated power and energy capacities of one PEV are 6 kW and 20 kWh respectively. Then the aggregated power and energy capacities of the PEVs connected to the parking lot is 300 kW and 1000 kWh respectively. Charging efficiency of all the PEV is set to 85%. The maximum and minimum SOC limits are set to 100 % and 20 % respectively. Table 1 shows the arrival and departure times of the PEVs in the residential area shown in Fig. 2, and at the parking lot [18].

Time interval of 33 hours was chosen with 1 hour time step ( $\Delta t$ ) for the simulations. This time interval was specifically chosen in order to cover one charging cycle of the PEVs. For the defined case, the optimization problem was solved with 11694 variables.

TABLE 1. ARRIVAL AND DEPARTURE TIMES OF THE PEVS.

| **Arrival** | | | | **Departure** | | | |
|---|---|---|---|---|---|---|---|
| **Residential area** | | **Parking lot** | | **Residential area** | | **Parking lot** | |
| T (h) | % | T (h) | % | T (h) | % | T (h) | % |
| 15 | 15 | 9 | 100 | 8 | 100 | 16 | 100 |
| 16 | 15 | | | | | | |
| 17 | 40 | | | | | | |
| 18 | 10 | | | | | | |
| 19 | 10 | | | | | | |
| 20 | 10 | | | | | | |

## V. RESULTS AND DISCUSSION

In order to verify the performance of our proposed algorithm, simulation results are dicussed to show firstly how the algorithm keep the voltage into the prefered bound, secondly how it sets proper charge times for fleet of vehicles either in residental area or parking lot with respect to wind, hydropower and PVs production and finally, how it minimizes the total cost.

Fig. 3 illustrates the hourly power productions of hydropower, wind power plant and PVs, which are injected into the grid at different buses shown in Fig. 1. It also includes hourly base load of system on Febuary 2nd , 2012. This a record peak demand for the year, and hence we simulate the worst case scnario and compare it with the results obtained from the case with PEV adoption.

Fig. 4 depicts the voltage fluctuations of critical points in the LV network (highlighted in Fig. 2). Dumb charging senario shows different pattern and voltage drops significantley. In this case, chargings start at arrival time accoring to Table I, without taking into account the critical situation of the system. It can be seen during hours 13-22, voltage magnitudes at nodes H50, H23, H02, H16 and H33 drop significatly. These abnormal voltage drops occur due to the fact that PEV charge and base load second peak happen at the same time. However, in optimal charging scenario, chargings are postponed around hours 26-30 and voltages are kept within normal operating range.

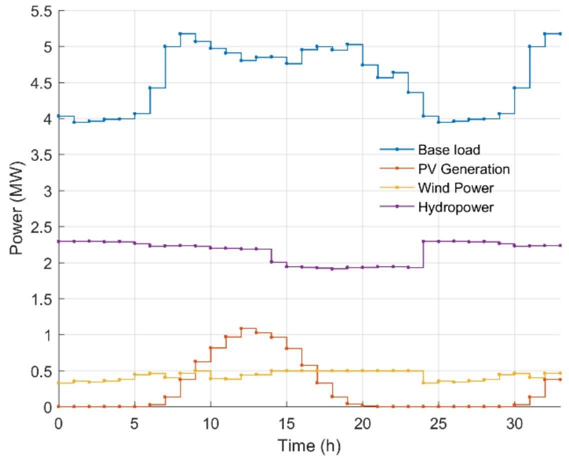

Figure 3. Hourly average generation of wind, hydropower, aggregated PV and load data.

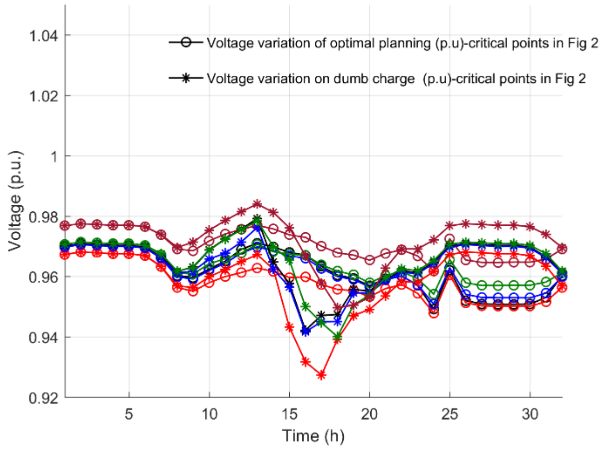

Figure 4. Voltage variation at the critical nodes of the network with time-horizon-ACOPF and dumb charging (Black: H50, Red: H23, Blue: H02, Green: H16 and Brown: H33).

Fig. 5 shows the hourly power exchange through feeder bus of the network with electricity prices specified by wholesale power market, which is Nord Pool, in the case of Norwegian system. It is clearly shown that charging in both parking lot and residential area are correlated with the lowest hourly electricity prices. However, charging power is only dependent on arrival time in the case of dumb charging scenario. Fig. 6 illustrates the charging pattern in the parking lot for both the optimal-charging scenario and dumb-charge scenario. Charging starts at low prices of wholesale market, which obviously minimizes total cost for DISCO to buy electricity from wholesale market. Fig. 7 illustrates the charge behavior and state of charge of PEVs located at residential area. It compares the results of the proposed algorithm with dumb-charging scenario. In Fig. 7-a, it is shown that charging occurs at the lowest marginal price around hours 25-31. However, it happens at arrival time for dumb charging scenario Fig. 7-b illustrates that the largest charge per hour can be 2.3 kW for optimal-charging and it is constant profile for dumb charging scenario.

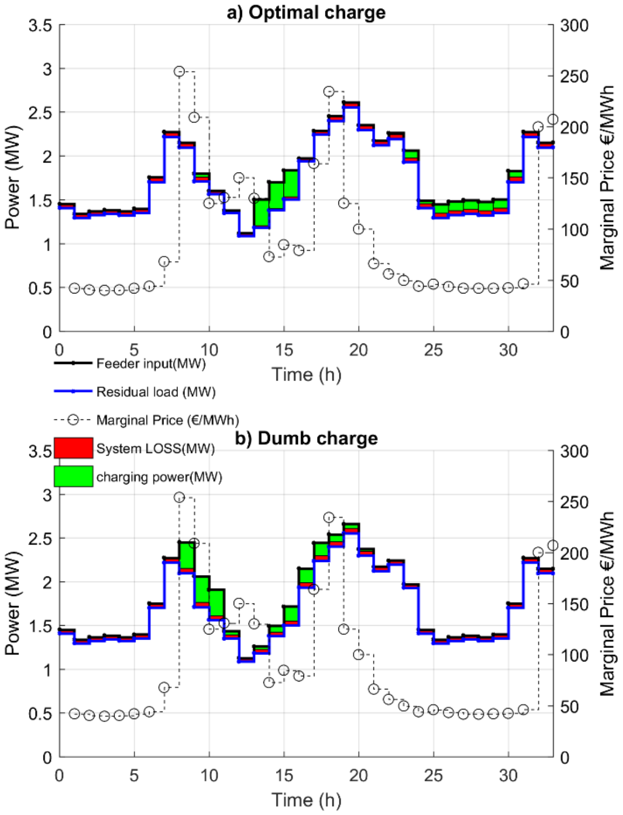

Figure 5. a) Optimal charging with the proposed algorithm, b) Dumb charging.

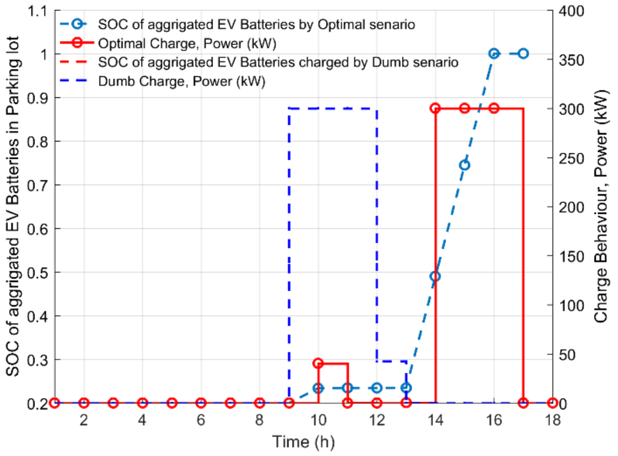

Figure 6. Charge behavior and the SOC of the EVs located at the parking lot with time-horizon-ACOPF and dumb charging.

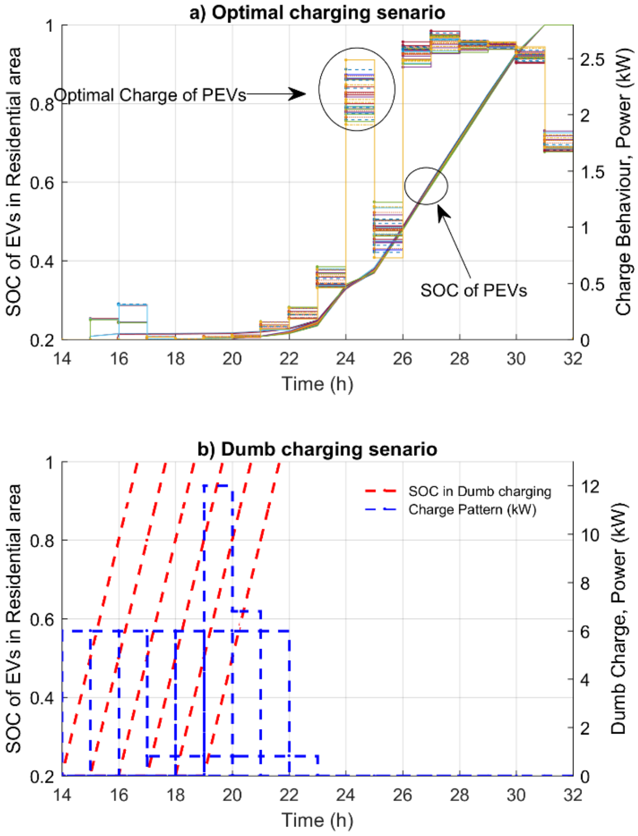

Figure 7. a) Charge behavior and the SOC of the PEVs located at the residential area with proposed algorithm, b) With dumb charging.

## VI. CONCLUSONS

The paper has presented the time-horizon-ACOPF algorithm including storage equations to simulate large-scale PEV penetration in a distribution grid including large number of distributed generators such as photovoltaics (PV), small wind generators and hydropower. The simulation results suggest proposed approach has some advantages over traditional dumb-charging scenario. First it minimizes the total cost of the system, and secondly it can be used to schedule charging to satisfy grid constrains such as voltage constrain, line and transformer overload constrains which are extremely important factors in LV network. Table 2 shows the total electricity cost bought from wholesale market in both simulation cases with our proposed method and dumb-charging scenario. This table indicates 2.4% of the total cost reduction in time-horizon-algorithm.

TABLE 2. TOTAL COST OF POWER IMPORTED FROM THE WHOLESALE MARKET.

| **Method** | **Total cost €** |
|---|---|
| Dumb-charging | 6096 |
| Time-horizon-ACOPF | 5949 |

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