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Assessment of predictive smart charging for electric trucks: a case study in fast private charging stations

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Abstract — Nowadays, the electrification of mobility and its charging by renewable energy sources has become a hot topic. In this regard, suitable solutions have been predicted for possible challenges in the presence of the high energy demand of passenger cars. Therefore, various charging algorithms with specific objective functions have been proposed for different applications. However, the emergence and growth of heavy electric vehicles such as trucks have a deeper impact on the local system, which reveals the need for more study in this field. In this paper, the impact of smart charging of electric truck as a flexible element in a fast-charging station of a factory is analyzed. The proposed predictive optimization charging algorithm for different uncontrolled, unidirectional and bidirectional scenarios tries to minimize the cost of energy exchanged with the grid. In this regard, considering the health of the battery, the best scenario from the factory owner's point of view is selected for a two-day interval including four different charge periods. Although it is obvious that the best scenario depends on the different parameters of each case study, the smart charging scenarios impose less cost on the local system in the desired case study.

Keywords—*Electric truck, Predictive control, Smart charging algorithm, State of charge, Unidirectional and bidirectional smart scenarios.*

I. INTRODUCTION

Electric vehicles are rapidly surpassing conventional vehicles, especially in developed countries [1], [2]. In fact, due to the need to reduce environmental pollutants and the increasing progress of technology, this transition is inevitable. In this regard, electrifying a large volume of electric vehicles with relatively same charging patterns is a big challenge for power networks. In other words, the high energy demand for charging electric vehicles in the morning and evening consumption peaks create an inappropriate load profile for the grid [3]. In this situation, there is a need for unreasonable investment to meet the load demand at peak points, which may be beyond the capacity of the grid. Therefore, the operator tries to encourage the consumers to move their unnecessary consumption to non-peak points. One solution is to increase the price of electricity at peak consumption points.

Recently, various intelligent charging algorithms have been presented in the literature to control charging and discharging of different scenarios for passenger cars [4]–[8].

For example, user-friendly smart charging was proposed in [5] for parking fleet scenario with modular converters. In addition, a technique was presented in [6] to limit the number of discharge cycles. In another work in [8], a Mamdani-based fuzzy strategy was developed to manage the output power of PEVs. However, the topic of large vehicles such as trucks and buses has been largely neglected. The number of electric trucks is increasing in the market, and their high power and energy density play an important role in network stability [9]–[11]. It is clear that the number of trucks is much less than the number of passenger cars, but their energy capacity is usually four to five times more than of an electric passenger car. Therefore, the presence of only one electric truck can provide smart charging conditions even for large consumers such as factories, offices, and buildings.

Electric trucks can offer benefits such as lower pollution, less maintenance, less noise, and better efficiency and performance. However, high initial cost, low driving range of full charge, long charging time, and finding a suitable charging station are disadvantages that make users hesitant. Renault Group has announced that it will launch various electric trucks in 2023 [12]. In this regard, various applications such as regional transportation, construction industry, and urban logistics have been considered to reduce the concern of various users as much as possible. For example, these products will have between 2 and 6 lithium-ion battery packs with energy between 180 and 540 kWh. Their charging time is also different depending on their type of charging (DC or AC), which normally travel up to 300 km with a full charge [13].

The use of electric trucks in the production and distribution lines of factories covers the above-mentioned challenges to a large extent. The use of dedicated charging stations, long parking time, and the need for a relatively reasonable driving range in these applications, along with the use of smart charging algorithms, can manage the factory's electricity consumption. In this paper, the smart charging of an electric truck belonging to a factory is investigated in two consecutive days in order to clarify the cost and benefit of meeting the user's needs for different scenarios. The rest of the paper is organized as follows: Section II describes a typical configuration of the desired charging station. Section III explains the proposed predictive smart charging algorithm in detail. Section IV presents the simulation results to assess the effectiveness of the proposed algorithm. Finally, Section V presents the conclusions of this paper.

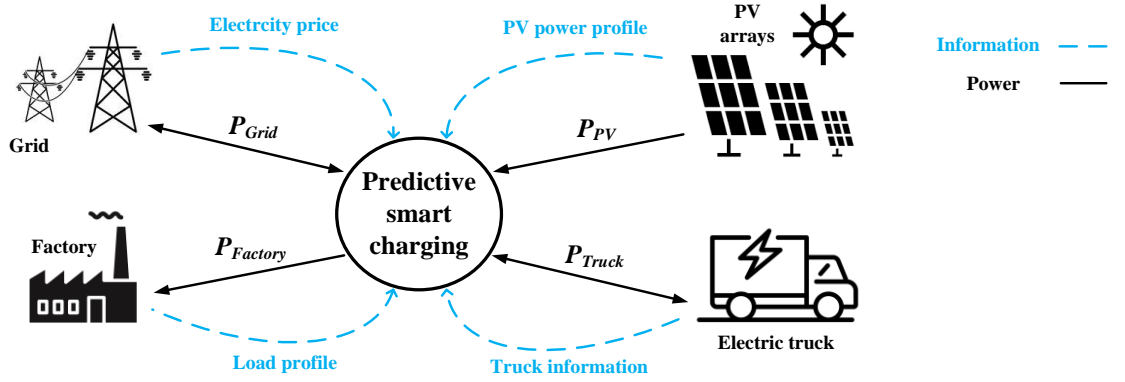


Fig. 1. Structure of the desired charging station.

TABLE I
ELECTRIC TRUCK SPECIFICATIONS

Symbol	Description	Value
$P_{Truck}^{max/min}$	Maximum/minimum truck power	150/-150 kW
E_{Truck}^{nom}	Nominal capacity of truck battery	240 kWh
$SOC_{Truck}^{max/min}$	Maximum/minimum truck SOC	90%/20%

II. DESIRED STRUCTURE OF CHARGING STATION

The charging behavior of electric trucks can be different from passenger cars due to shorter breaks, higher charging power, and long driving distance. It should be noted that accurate information on electric truck charging is still rare [14], [15]. In fact, lack of need and lack of extensive development has delayed a comprehensive examination of their behavior.

In this paper, as a case study, the fast charging station of an electric truck in a factory in the suburbs is considered as shown in Fig. 1. In fact, this factory needs a truck to produce and distribute its products, where the electric type of that can be more useful in coordination with other electrical equipment. The power consumption profile of this factory has a peak power of 50 kW in the evening. Also, this factory is equipped with photovoltaic arrays with a maximum power of 70 kW, which can be used for factory consumption, vehicle charging, or injection into the grid. The price of electricity is dynamic and based on consumption, with two main peaks in the morning and evening to encourage the consumer to make unnecessary consumption at a low price. The full specifications of the desired electric truck are presented in Table 1, and its different charging scenarios will be examined in two consecutive days. Before presenting the proposed predictive algorithm, it is necessary to consider the information of charging, discharging, and truck arrival and departure times for two days.

According to Table II, it is assumed that the electric truck will be present at the charging station after the first midnight with an initial charge of 40% for the first charging period. According to the specified schedule, the truck should be prepared with a maximum charge (90%) for distribution in the morning. In this distribution, the truck is outside the factory for 4.5 hours and returns to the charging station with a 25% battery charge for the second charging period on the first day. Now, the truck should be prepared for evening shift distribution. In the evening shift, due to the shorter working time, a lower final charge equivalent to 70% is needed. After the evening work shift for 3.5 hours, the truck is at the charging station of the factory. During this long parking period (13 hours) that will last until the next morning, the truck can be charged or even discharged based on the objective function and constraints. On the second day, two almost similar work shifts are planned for the electric truck in the morning and evening. On returning from the evening shift on the second day, the truck must be prepared again for the third day, which is therefore not included in the proposed charging schedule.

III. PROPOSED SMART CHARGING ALGORITHM

As stated, typically the power grid operator tends to use variable electricity price to encourage consumers to shift their unnecessary consumption to off-peak times. Therefore, the desired factory tries to control its electricity consumption in such a way to minimize costs. In this regard, the load profile curve of the factory can be predicted in advance, which must be fully supplied. It should be noted that the consumption load can also be managed based on the price of electricity. According to in-depth studies in this field, it is assumed that appropriate solutions have been applied in a previous step on the load profile, which is not the main topic of this paper [16]–[18]. The production power of photovoltaic arrays is used in its maximum amount for internal consumption or injection into the grid. The power grid is also responsible for establishing a balance between production and internal

TABLE II
ELECTRIC TRUCK CHARGING INFORMATION

	Arrival time	Departure time	SOC_{init} (%)	SOC_{final} (%)	Parking time	Next distribution time period
Charging 1 First day	00:10	07:00	40	90	06:50	04:30
Charging 2 First day	11:30	15:00	25	70	03:30	03:30
Charging 3 First and second days	18:30	07:30	20	90	13:00	03:00
Charging 4 Second day	10:30	14:00	30	70	03:30	04:00

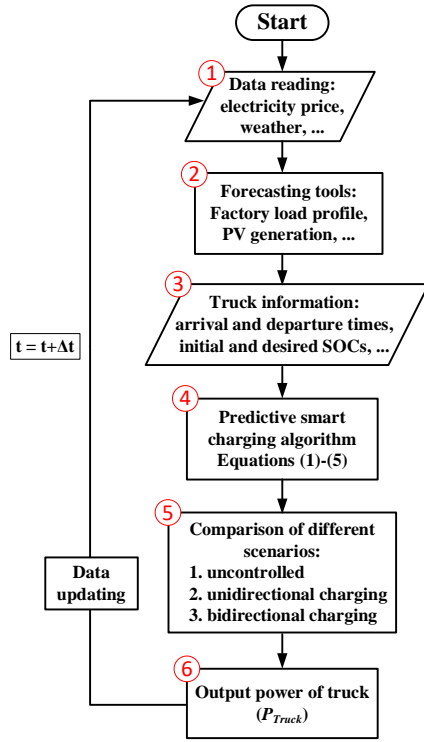


Fig. 2. Flowchart of the proposed smart charging algorithm.

consumption of the factory, and the cost of power exchanged with it is calculated based on the price of electricity. Finally, there is an electric truck as a flexible element in the desired system. In fact, when the truck is at the charging station it can reduce costs by charging and discharging on time [19]. In this regard, the algorithm proposed here is inspired from [20], which was suitable for passenger cars. In the proposed prediction algorithm in this paper, which is shown in Fig. 2, based on the available information, the optimal power of the truck is predicted for the next 20 hours. This output power is transferred to the charger controller and is updated every 5 minutes due to different uncertainties. According to the desired objective function in equation (1), the cost of energy exchange with the utility grid (C_{total}) is minimized assuming battery efficiency.

$$\begin{aligned}
 \text{Minimize } C_{total} = & \underbrace{\sum_t \text{Price}(t) \times \Delta t \times P_{Grid}^{Pos}(t)}_{\text{first term - energy purchase}} + \\
 & \underbrace{\sum_t \text{Price}(t) \times \Delta t \times 0.9 \times P_{Grid}^{Neg}(t)}_{\text{second term - energy sales}} - \\
 & \underbrace{\sum_t \text{Price}(t) \times \left[\underbrace{P_{Truck}^{Pos}(t)}_{\text{charging}} + 0.9 \times \underbrace{P_{Truck}^{Neg}(t)}_{\text{discharging}} \right]}_{\text{third term - battery efficiency}}
 \end{aligned} \quad (1)$$

where $\text{Price}(t)$ is the real-time electricity price, Δt is optimization time step, P_{Grid}^{Pos} is positive power exchange with grid, P_{Grid}^{Neg} is negative power exchange with grid, P_{Truck}^{Pos} is discharging power of electric truck, and P_{Truck}^{Neg} is charging power of electric truck.

In other words, the first term indicates the purchase of energy from the grid, the second term indicates the sale of energy to the grid with 90% of the proposed price, and the third term indicates the efficiency of the truck battery in

charging and discharging, which is considered equal to 90%. It should be noted that there are also various constraints such as truck charging power limit, truck energy capacity limit, balance equation, and the desired final energy according to equations (2)-(5) in the algorithm.

$$\text{Subject to } P_{Truck}^{\min} \leq P_{Truck}(t) \leq P_{Truck}^{\max}, \quad (2)$$

$$SOC_{Truck}^{\min} \leq SOC_{Truck}(t) \leq SOC_{Truck}^{\max}, \quad (3)$$

$$P_{Truck}(t) = P_{Factory}(t) - P_{Grid}(t) - P_{PV}(t), \quad (4)$$

$$E_{Truck}(t) = \begin{cases} SOC_{init} \times E_{Truck}^{nom}; & t = t_{arr} \\ E_{Truck}(t - \Delta t) - P_{Truck}(t) \times \Delta t; & t_{arr} < t < t_{dep} \\ SOC_{final} \times E_{Truck}^{nom}; & t = t_{dep} \end{cases} \quad (5)$$

It should be noted that in this structure, unlike passenger cars, information about the next charging periods of the truck can also be available. In fact, as stated in the previous section, according to the work shifts and driving routes, the truck charging information can be extracted for at least the next two days. Therefore, the proposed algorithm is also considered for the two-day interval, which includes four different charging periods. Also, unlike the previous algorithms for passenger cars, in this structure, the owner of the charging station and the truck owner are same that does not need to be informed and choose a scenario. In other words, the proposed algorithm can be adjusted to choose the best scenario.

In general, the smart charging algorithm can be implemented as unidirectional or bidirectional. In the unidirectional smart charging scenario, only the charging of the electric truck is controlled, but in the bidirectional smart charging scenario, the discharging of the electric truck is also considered along with its charging. The main concern in using bidirectional smart charging is serious damage to the truck battery, which can reduce its useful life. In this paper, the best case of each scenario is obtained and by comparing the battery health, the best scenario is applied to the truck. Also, to better check the performance of the proposed algorithm, the results of uncontrolled truck charging are also provided, which are immediately charged with maximum available power to the desired level.

IV. SIMULATION RESULTS

In this section, the desired structure is simulated in Matlab/Simulink software to check the performance of the proposed algorithm. Here, it is assumed that PV production power, electricity price and factory load are the same in two consecutive days. In this regard, three different scenarios include uncontrolled, unidirectional and bidirectional are implemented.

In the first simulation, the results for the uncontrolled scenario are shown in Fig. 3. In this regard, the output power of different elements of the system (PV, grid, load and electric truck), truck SOC, time-varying electricity price and finally the cumulative cost of energy exchange with the grid are presented. As expected, there are four charging periods in the uncontrolled scenario, which start charging immediately after the truck arrives at the station with maximum available power. It should be noted that in this structure, the grid power is limited to 100 kW, which limits the power consumption of the truck. Also, although three charging periods are randomly performed at the appropriate electricity price, one period (the third charging period) will be performed at the maximum

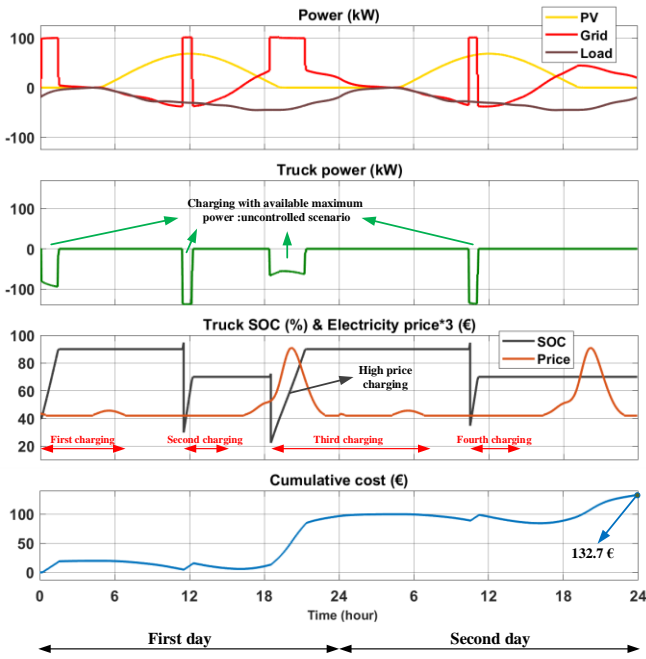


Fig. 3. Uncontrolled charging scenario results.

electricity price. The sudden drop in SOC of the battery is also related to the truck entering the charging station after the distribution work shifts, when the battery is discharged according to the route traveled. At the end of these two days, 132.7 € must be paid to the network for energy exchange.

In the second study, the results related to unidirectional smart charging are presented in Fig. 4. In this scenario, it is tried to charge the truck at the minimum price of electricity and make maximum use of the local production power. According to Fig. 4, the first charging of the truck starts with a slight delay compared to the previous scenario in order to pass the midnight price peak. Due to the departure time at the beginning of the morning, the most required charging is done at the beginning of midnight with the maximum power at the minimum price. A small charging is also planned according to the production power of PV at the beginning of the morning so that the truck with the desired final energy is ready for the morning distribution shift. In the second charging period, due to the sufficient PV production power, the truck will be fully charged by PV arrays and the energy exchange with the grid will be zero during this period. However, the biggest difference compared to the previous scenario is in the third charging period. During this period, the charging of the truck is postponed to pass the significant price peak. Also, there is a small peak at the beginning of the midnight, which due to enough time, the charging of the truck stops in this short period and the charging is slightly moved to the beginning of the morning. In the last charging period, the PV production power is again used to fully charge the truck. The cost of energy exchange with the grid in this scenario is equal to 109.6 €, which shows a 17.4% reduction compared to the previous scenario.

As a final study, the simulation results of bidirectional smart charging are shown in Fig. 5. In this scenario, truck battery discharge is used in all price peaks. In the first charging period, the behavior is almost similar to the previous scenario, along with discharge at midnight and morning peak points. The second and fourth charging periods are completely similar to the previous scenario. However, the biggest difference is

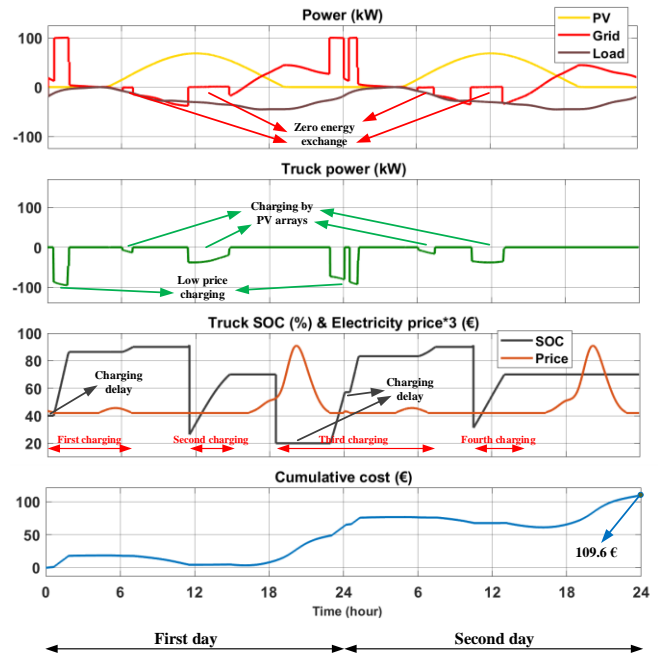


Fig. 4. Unidirectional smart charging scenario results.

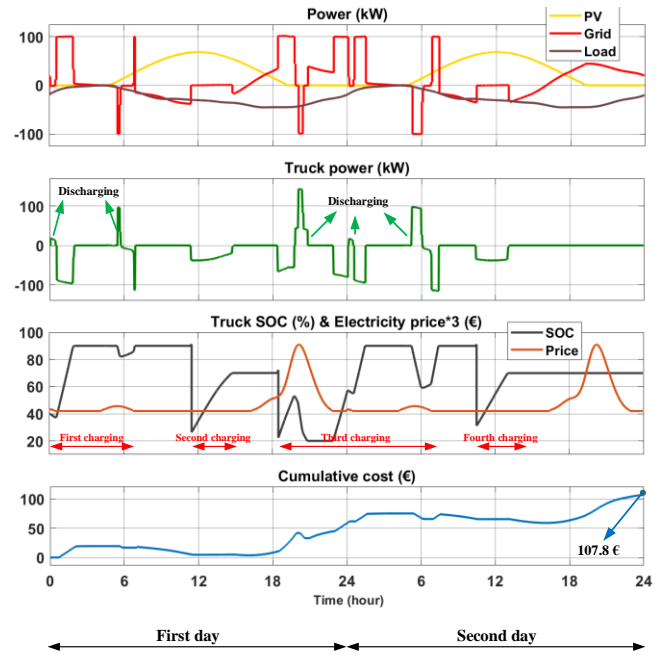


Fig. 5. Bidirectional smart charging scenario results.

again in the third charging period when the battery is discharged to the minimum energy (20%) to return the most profit to the factory. Also, during this period, there is a battery discharge during the price peak at midnight and at the beginning of the morning. Finally, in this scenario, the energy exchange cost with the grid is equal to 107.8 €, which shows a decrease of 18.8% and 1.6% compared to the first and second scenarios, respectively. These results obtained from the above simulations are summarized in Table III. It should be noted that it is a fact that the best-case scenario varies for different case studies depending on the system parameters such as local load power, the number of trucks, and etc.

V. CONCLUSION

In this paper, an intelligent predictive charging strategy for electric truck was presented. Typically, electric trucks are of

TABLE III
COMPARISON OF DIFFERENT SCENARIOS

	Uncontrolled scenario	Unidirectional scenario	Bidirectional scenario
Energy exchange cost with grid (€)	132.70	109.60	107.80
Smart charging	no	yes	yes
Effective grid support (V2G)	no	no	yes
Charging by PV arrays	no	yes	yes
Low price charging	no	yes	yes
PEV Charging time	fast	it depends	it depends
Optimization time	fast	medium	slow

interest to large factories for product distribution, which will have a significant impact on the charging station, unlike passenger cars. In this regard, it was shown in a case study that by using smart charging of electric trucks, the cost of electricity in the factory can be better managed. The coordination of different elements of the system, including PV arrays, local consumption, electric truck and power grid, was investigated for unidirectional and bidirectional smart scenarios. It should be noted that it is a fact that the best-case scenario varies for different case studies depending on the system parameters. In the desired structure, according to the assumptions of the problem, bidirectional and unidirectional smart scenarios reduced the factory electricity cost by 18.8% and 17.4%, respectively, compared to the uncontrolled scenario. In these scenarios, the electric truck was used as a flexible element in energy consumption or storage. Therefore, it is anticipated that with the development of electric trucks for various applications, the application of smart charging to utilize their flexible capacity is inevitable.

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