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A Rule-based Method for Efficient Electric Vehicle Charging Scheduling at Parking Lots

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Abstract. Electromobility is being promoted to reduce the greenhouse gas emissions. To this extend, and through the technical advancement of electric vehicles (EVs), EVs are increasing in a fast pace. However, their charging could impose problems to the distribution network, local substations and transformers. This holds true especially in charging stations with a high number of EV chargers, such as the parking lots. To address this, a rule-based algorithm is proposed in this paper to minimize the charging cost, participate in a demand response program, and simultaneously satisfy the technical and operational constraints of the EVs and parking lot's local transformer. The proposed rule-based algorithm is compared with the case of uncoordinated charging and with an optimization-based charging schedule based on the particle swarm optimization (PSO). The obtained results indicate that even if the charging cost with the proposed algorithm is not significantly reduced compared to the PSO charging strategy, the executed time is significantly lower. Comparing with the uncoordinated charging, the proposed algorithm has a lower charging cost and a similar execution time.

Keywords: electric vehicles; energy management system; demand response; efficient charging scheduling; vehicle-to-grid; distribution network

1. Introduction

1.1. Motivation

In the effort of reducing the greenhouse gas (GHG) emission, the increase in the electrification of the transportation sector is a crucial factor, as the sector represents 21.5% of Europe's GHG emissions [1]. EVs penetration is increasing year by year and their charging concerns the scientific community and distribution system operators, as it could create new congestion and demand peaks, voltage quality problems etc. Especially, the parking lots (PLs) that would facilitate a considerable number of EV chargers, making them a potential "troublemaker" for the operation of the grid. However, many of the issues that EVs charging creates, could be addressed by coordinating their charging or even Vehicle-to-Grid (V2G) services [2].

1.2. PhD work relation to the conference theme

Energy, which is one of the topics of interest of the Advanced Doctoral Conference on Computing, Electrical and Industrial Systems 2022, is a very interesting subject, especially in crisis time periods. The energy demand is increasing more and more through the years. Energy management in order to exploit the available energy and electric grid efficiency is imperative if we aim to keep a sustainable future. This is the reason why this PhD work deals with the electricity distribution and the required coordination of the EV chargers in the electricity network. The work in this paper consists a part of this PhD project and gives an insight into managing EV charging at a PL.

1.3. Literature review

Smart charging of EVs at PL has thoroughly been examined in the literature taking into consideration various methodologies, scenarios and objectives. Coordinating the EV charging process in order to prevent the overloading of the PL's local transformer and generally the local distribution grid while at the same time achieving minimization of the charging costs is a challenging but possible task, as the EV's charging load could be characterized as shiftable and interruptible.

In this sense, the authors in [3], developed a centralized charging schedule of EVs at a PL and used the Advanced Interactive Multidimensional Modeling System software to maximize the profit of the PL. Realistic mobility/parking patterns were taken into consideration but only slow charging was considered. The main objective in [4] was the valley filling and peak shaving of power consumption in a non-residential system. It was achieved by scheduling suitable the EV charging and discharging. In [5], a real-time fuzzy logic based charging scheme with V2G capability was proposed in order to manage the charging loads of EVs in a PL and to minimize the charging costs. The charging/discharging priority of each EV was calculated depending on the state-of-charge (SoC), remaining charging time and electricity price. In [6] the authors developed a particle swarm optimization (PSO)-based EV charging schedule considering the discharging of EV's. Their objective was to minimize the cost and the charging time at different scenarios, i.e., considering electricity price, and microgrid total cost. In [7], an EV charging schedule is proposed and PSO is used to minimize the PL charging cost. In [8], a simple multi-parameter method was developed in order to minimize the EVs charging cost at a PL, considering electricity price and distribution load. Moreover, PSO was used to obtain the charging schedule of EVs.

Indeed, classical optimization-based approaches have been examined in many studies. However, some rule-based approaches for coordinating EV charging schedule have also been discussed. In particular, rule-based algorithms may be preferred for the implementation of energy management schemes, as they provide exact solution to the desired output conditions, computationally efficiency and are preferable for real-time applications [9]. In particular, in [10], the authors developed a rule-based energy management scheme for EV charging in order to provide uninterrupted charging at a

constant price under a different number of office working days. Valley filling of power consumption and the financial model for a PL with photovoltaic and energy storage system was examined, too. Finally, V2G technology could reduce the payback period of the existing system but, the satisfaction of the charging targets of all EVs are not guaranteed. In [11], a simplified charging strategy is proposed to improve the load profile for commercial building microgrids accommodating PV and EV. The proper allocation of PV power and EV charging was assigned according to priority rules without taking into consideration V2G services.

1.4. Contributions

The main contributions of this paper are summarized as follows:

- The EV charging scheduling algorithm proposed in this paper is simple and efficient. No forecast or other possibly expensive devices for the optimal solution calculation are needed.
- The algorithm takes into consideration all the constraints of the EV charging process (minimum and maximum SoC, charging rate limitation) and satisfies the charging requirements of all EVs. Moreover, the proposed charging strategy is compared with an optimization-based charging strategy (PSO) and an uncoordinated charging giving better results. More specifically, it is faster enough than the PSO charging scheduling and furthermore delivers better cost results compared to both basic charging strategies (PSO and uncoordinated).
- The proposed charging algorithm can participate in demand response (DR) program by reducing its total consumption. The amount of power that can be reduced, without violating any charging constraints, can be easily estimated.

2. Parking Lot Model and System Parameters

To evaluate the effectiveness of the proposed charging method, over the standard optimization algorithm of particle swarm optimization (PSO) as well as the case of uncoordinated charging, we model a representative PL equipped with EV chargers.

2.1. Parking Lot Model

A PL with EV chargers, adequate to serve all the incoming EV, was assumed. The arrivals, parking duration of the EVs and residual state of charge of each arriving EV (SoC_{Arr}) were estimated as in [12].

2.2 EV and charger type

Ten representative model of EVs were used (Tesla Model 3, Renault Zoe, Hyundai

Kona Electric, Nissan Leaf, Volkswagen e-Golf, Peugeot e-208, Audi e-Tron, Kia e-Niro, BMW i3, Volkswagen e-Up!). Their possibility of appearance of each type of EV in the parking lot is estimated from [13], depending on their sales. In addition, the PL was considered to include four types of EV charging stations. Their types and power rate are shown in Table 1. It was considered that all charging stations and EVs could support bidirectional energy flow. Finally, the charging efficiency (ce) was considered 0.93 and it represents the losses from cabling, EV battery and conversion losses during the charging and discharging process.

Table 1. Chargers types and power rate.

Charger type	Power Limit
1-ph-32A (AC)	$-7.4 \text{ kW} \leq \text{Power} \leq 7.4 \text{ kW}$
3-ph-16A (AC)	$-11 \text{ kW} \leq \text{Power} \leq 11 \text{ kW}$
3-ph-32A (AC)	$-22 \text{ kW} \leq \text{Power} \leq 22 \text{ kW}$
Combined Charging System (DC)	$0 \text{ kW} \leq \text{Power} \leq 100 \text{ kW}$

3. The benchmark and proposed charging strategies

Depending on the charging strategy that would be applied, the economical and operational benefits are varied. For developing the proposed strategy, the time horizon was divided into time slots with length $\Delta t = 1 \text{ h}$.

3.1. Charger Type and Power Limit Selection

Depending on the parking duration and EV's charging power converter, a suitable charger type was selected to be plugged in. As a first step, it is checked in which AC charger type could be plugged in depending on the EV's AC charging power converter. Follows the check if the EV would charge at an AC charger, that was chosen in the previous step, or at a DC charger as shown in Equation (1). If the EV is connected to a DC charger, discharging is not considered as an option.

$$\text{Charger} = \begin{cases} \text{AC charger,} & E_{\max}(i) \geq E_t(i), \\ \text{DC charger,} & \text{otherwise} \end{cases}, \quad \forall i \in \text{EV} \quad (1)$$

where $E_{\max}(i)$ is the maximum energy that the specific type of charger could give to the i th EV if it operates with its nominal power during the parking duration and $E_t(i)$ is the energy required for the i th EV to reach its desirable SoC. The power limit of each charger is depending on its charger type and the EV's on-board charger limitations, and it is estimated in the following Equation:

$$-P_{\text{limit}}^{\text{Charger}}(i, t) \leq P(i, t) \leq P_{\text{limit}}^{\text{Charger}}(i, t), \quad t_A(i) \leq t < t_D(i), \quad \forall i \in \text{EV} \quad (2)$$

where $P_{limit}^{charger}$ is the nominal power of the i th EV's charger at the t time slot, t_A and t_D is the arriving and departure time of the i th EV, respectively. In the sequel, the two benchmark (uncoordinated and PSO) strategies as well as the proposed rule-based algorithms are presented.

3.2. CS1: Benchmark Uncoordinated Charging

As uncoordinated charging is defined the process where the EV users arrive at the PL, plug in their EV and the charging process starts immediately with the maximum power of their EVs charging power limitations.

3.2. CS2: Benchmark PSO Charging

The PSO function of Matlab was used to optimize the charging process of the EVs in the PL. The objective function that was used takes the form:

$$F(i) \left(\sum_{t_A}^{t_D-1} P(i,t) \cdot T \cdot (ce\ cha(t) - dis(t)) \cdot EP(t) \right), \quad \forall i \in EV \quad (3)$$

where cha and dis are binary variables and set to 1 when the EV charge or discharge, respectively. The battery stored energy constraints of the lower and upper limits are taken into consideration during the whole process. As battery lower and upper limit are considered the 20% and 100% of the battery capacity of the EV, respectively. Furthermore, the desirable state of charging is shown in Equation (4).

$$\sum_{t=Arr}^{Dep-1} P(i,t) \cdot \Delta t \cdot (ce\ cha(t) - dis(t)) + E_A(i) = E_t(i), \quad t_A(i) \leq t < t_D(i), \quad \forall i \in EV \quad (4)$$

where E_A is the residual energy of the i th arriving EV's battery.

3.3. CS3: Proposed Rule-Based Algorithm

The idea of using rule-based charging strategy is simple. More specifically, it is assigning the charging process in the time slots where the electricity price is low and the discharging of the battery of the EVs the time slots where the electricity price is high.

At first, the time slot with the lowest electricity price is searched and it is assigned the maximum power or part of the charger power limit depending on the SoC_t . In case that it requires another time slot to satisfy the charging target, the same process takes place until the EV reaches the desirable departure SoC .

As a next step, it is checked if the discharging process is profitable. Then, an opposite process takes place. Particularly, the time slot with the lowest and highest

electricity price and, in which the charger does not operate in its nominal power are identified in order to perform charging in the first and discharging (V2G) to the second.

Furthermore, in case that the PL has a power limitation, e.g., due to a local MV/LV transformer, an extra check is added to the proposed rule-based algorithm. Note that the EVs were divided into two categories, flexible and inflexible, depending on their capability to change their charging schedule without delaying their departure. After the charging scheduling in each time slot has been completed, the total power consumption of the PL is calculated. In the case that consumption exceeds the power limit (when assuming one), the following process takes place. At first, the flexible and inflexible EVs are estimated. Inflexible EVs are defined those that the PL's power violation happens at the last time slot of their charging. At the power limit violation time slot, the available power is proportionally distributed to the flexible EVs, following the Equation (5). Note that, available power is defined by the power limit minus the sum of the inflexible EV charger power.

$$P(i, t) = P_{Flex}^{old}(i, t) \cdot \frac{P_{Lim}}{P_{Flex}(t)}, \quad t \in T_{Violation}, \quad \forall i \in EV_{Flex} \quad (5)$$

where P_{Flex}^{old} is the charging power that was assigned to the charger of the i th flexible EV at the t time slot before the PL's power violation check is triggered, P_{Flex} is the sum of all flexible EVs' charging power at the power violation time slot, P_{Limit} is the available power, i.e., the power limit of the local transformer of the PL, $T_{Violation}$ is the time slot that the power violation occurs and EV_{Flex} is the flexible EVs. In addition, inflexible EVs where also those EVs which, when their charging schedule change in the power violation time slot, they cannot reach their charging target with the new charging scheduling. In Fig. 1, the process that takes place when power violation happens is described. Note that in the step "New charging scheduling", the EVs' charger power that it is estimated in Equation (5) at the time slot that the power violation happens is assigned. Moreover, for the remaining parking duration the charging schedule of the EV is calculated as it was explained above, before the power violation happens. Finally, the power limit of the PL is insufficient when all EV characterized as inflexible. In particular, there is not adequate power in order to cope with the power limit violation without delaying the departure or not satisfying the SoC target of some EVs. In this way, it can be estimated the lowest power limit of the PL, which can be assigned to the PL, without changing the EV drivers' preferences.

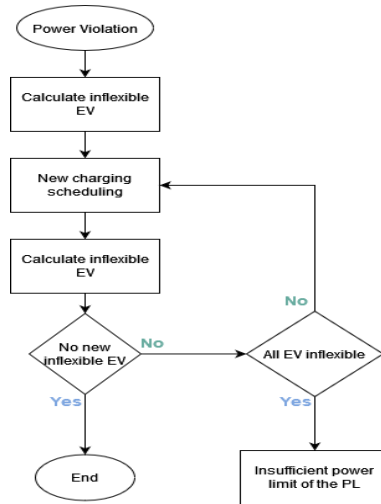


Fig. 1. Charging process when the power limit of the PL is violated.

3. Results

To evaluate the performance and efficiency of the proposed strategy multiple scenarios were created. The simulations were conducted in a computation system with processor Intel(R) Core (TM) i5-3470 CPU @ 3.20GHz and RAM 8 GB. The electricity price time series were obtained from the independent power transmission operator (IPTO), Greece [21] and they are shown in Fig. 2.

3.1. Comparison between charging strategies

The PL's local transformer capacity was not taken into consideration when the charging strategies were compared. The proposed algorithm for the charging of the EVs at a PL showed a better efficiency than the other two charging strategies in all scenarios. The mean charging cost of the proposed charging strategy for 10 operation scenarios is 0.99% and 6.25% better than that of CS1 and CS2, respectively. Although the charging cost when the proposed charging strategy was applied was lower, it did not show considerable difference compared with the PSO case. However, the mean executed time for each EV, at all the examined period, of the proposed charging strategy was 0.014 seconds and in the case of PSO 13 seconds.

Hence, it can be concluded that the proposed charging strategy could be applied in real-time problems with uncertainties as it can respond faster by calculating the EV charging schedule at short time periods. Finally, no expensive device for the calculation process is needed because of the simplicity of the algorithm.

3.2. CS3 when the PL's transformer capacity was considered

The nominal power of the PL's local transformer was considered 1500 kVA. The operation scenarios had similar results, so a random scenario was chosen to show the behavior of the CS3 when the PL's transformer and DR program were considered. During the examined period 715 EVs were charged. The PL's active power when CS3 is applied and i) no power limit is considered (case A), ii) power limit of the transformer (case B) and iii) power limit of the transformer and DR (case C) are considered, is depicted in Fig. 2.

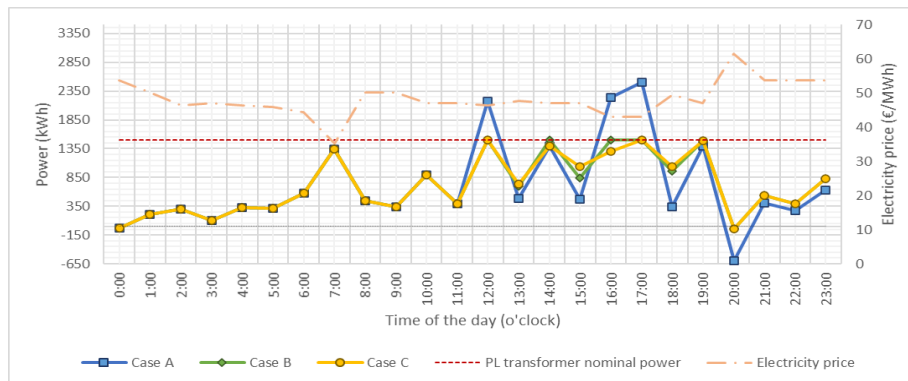


Fig. 2. PL's active power and electricity price.

In case A, it can be observed in Fig. 2 that the PL's active power and electricity price are correlated, as the charging process was mostly arranged when the electricity price was low, while the discharging process correspondingly occurred when the electricity price was high. In addition, the charging cost of the PL was 887.49 EUR.

In case B, it can be observed in Fig. 2 that the PL's active power and electricity price are correlated as long as the power limit of the PL is not violated. Moreover, it can be observed that the power that was reduced, because of the power limit, was shifted in the next or the previous time slots. The energy sold to the grid was reduced because there was not enough available power to charge the batteries adequately and later discharge (V2G) them at the time slots that it would be profitable. Additionally, the charging cost of the PL was 901.63 EUR, and it was, as expected, higher than the case A. This happened for two reasons, the energy that was sold to the grid was lower, and by applying the power limit it was not fully exploit the time slot in which the electricity price was low. Case C was similar with case B. In addition, at 14:00 and 16:00 o'clock the PL's active power limit was reduced at 1400 kVA and 1300 kVA as a demand response service, respectively. In this case, the charging cost of the PL was 902.65 EUR. The application of the transformer capacity and DR did not affect considerable (1.68%) the daily charging cost, but it is a more realistic case as the PLs

have power limitation. Furthermore, demand response program could return profits as it is a service that the client who use it, is getting paid for it.

4. Conclusion

In this paper, a rule-based algorithm for coordinated charging of EVs at a PL is proposed. To evaluate the performance of the proposed algorithm, it has been compared with two charging strategies which use the PSO function of Matlab as well as the case of uncoordinated charging. Results show that the proposed algorithm achieved the minimum charging cost, satisfied all the constraints and at the same time the executed time was short enough to be applied at short time slots as a demand response tool and support the distribution network.

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